Emergy Analysis and Supply Chains
A Circular Economy Byproduct Supply Chain Case Study

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ABSTRACT

The circular economy (CE) has grown in global importance, in part because of its capacity to address various environmental concerns. It is critical to better understand its structural, policy, and managerial implications—both environmental and economic—and integrative performance measures can help achieve such understanding.

Emergy analysis (EA) (with an ‘m’) has been receiving increasing attention for its applications in environmental accounting, where it serves as an integrative performance measurement tool. Its relationships with, and implications for, sustainable supply chains and the CE are not yet well understood, despite initial investigations; emergy analysis may potentially provide profound opportunities for advancing these sustainability-oriented fields. Emergy analysis uses donor-side valuation approaches as a basis for economic, social, and environmental performance measurements.

Based on an environmentally oriented theoretical foundation, this thesis aims to extend the applications of inherently broad environmentally integrative performance measures in CE at the supply chain level. It offers a comprehensive measuring tool that can be part of the organizational decision-making process. Furthermore, this dissertation thesis study integrates certain external pressure aspects expressed by two government policies, altering the performance of the supply chain under study.

For the purpose of gaining a deeper understanding of sustainable supply chain management (SSCM) and CE performance, this research investigated the viability of potential integrative methods addressing CE supply chain issues. An integrative emergy system dynamics methodology is applied to address supply chain-related decisions while incorporating a theoretical perspective that uses the natural resources dependence theory (NRDT). EA is used to evaluate two different

multitier supply chains using a CE by-product practice, wherein by-products are former waste products transformed into useful, value-adding materials.

A case study evaluation as a proof-of-concept focuses on Saudi Aramco's supply chain processes of lost circulation materials used in drilling operations. Lost circulation materials are small particles used to plug and fill the cracked rock formations found underground to minimize drilling fluid waste. Saudi Aramco formerly imported walnut shell by-products from the United States for use as lost circulation material. In recent years, however, date seed by-products have been introduced to completely replace walnut shell by-products, given their local availability as well as the scale of the date industry in Saudi Arabia. The supply chain emergy evaluation includes the cultivation, transportation, and remanufacturing of the tested by-products.

In addition to EA, an SD model was constructed using Stella Architect software. The SD model presented the emergy system of date cultivation, which is part of the date seed by-product supply chain. The SD model is used as a policy intervention tool to simulate four scenarios that investigate the impact of two government policies on the emergy evaluation of date cultivation. These policies are the government subsidy and the environmental concerns policy. The approach used here relates to external regulatory pressures and how they can be captured in NRDT through this emergy-based SD methodology.

Finally, this research presents donor-side indicators as a practical means of measuring the components of NRDT, which together make up the reciprocal relationship that exists between the natural environment and organizations.

Results of the emergy analysis suggest that the walnut shell by-product supply chain performs more sustainably than the date seed by-product supply chain. The emergy-based indicators show that date production (the origin of the evaluated by-product) imposes a higher environmental burden, as measured by emergy loading ration (ELR), compared to walnut production.

The simulation results of the emergy SD model revealed that integrating the two suggested policies produced the best emergy performance by improving the emergy-based indicators over time. A series of general research propositions based on our study results are presented in the interest of potential avenues for future research.

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CHAPTER 1 : INTRODUCTION

This chapter introduces the primary issue that motivates this dissertation thesis, beginning with an overview of the problem statement that is supported by current literature.

As globalization increases the complexity of supply chains, their environmental performance becomes extremely difficult to assess and address. As supply chains expand globally, many challenges arise. In particular, transportation management is increasingly challenged to curb environmentally problematic rises in energy consumption and CO_2 emissions (Khan et al., 2017a).

Currently measured in terms of financial and business performance, supply chains face mounting pressure to become more sustainable (Jabbour et al., 2020; Taticchi et al., 2015). Being "sustainable" means focusing on measures and concerns that go beyond the typical financial and business bottom lines, expanding to social and environmental performance (Gouiiferda and Mounir, 2022; Seuring, 2013).

Although significant research has focused on expanding the performance of sustainable supply chains to include these additional dimensions, weaknesses persist (Jabbour et al., 2020). Because environmental sustainability has been difficult to measure with current systems, outcomes have tended to be misleading or unreliable; broader as well as focused environmental accounting can address these issues (Tian and Sarkis, 2020). *Emergy* (with an 'm') is the measure used in an emergent scientific accounting system using ecological indicators that may help advance understanding, research, and practice in sustainable supply chain management (SSCM) and green supply chain management (GSCM) (Tian and Sarkis, 2020; Young et al., 2012).

Integrations of emergy analysis (EA) with other performance measures have been promoted to augment its practical and research applications. Due to EA's systemic characteristics, challenges may exist with utilization and interpretation in some tools. This emergent measure has attracted interest in ecological indicator research (Karuppiah et al., 2022; Xu et al., 2022). It has also been applied to some economic and business systems, although it has seen only limited use, despite its advantages at the organizational and supply chain levels within a circular economy (CE) context (He et al., 2020; Panchal et al., 2021).

The central problem of this research is driven by current limitations within the existing body of literature. First, as supply chains become increasingly complex and integrated with CE principles, the need to expand related evaluation metrics and measures is also growing (Datta and Diffee, 2020; Narimissa et al., 2020a, 2020b; Nikolaou et al., 2019). From a practical viewpoint, without accurate and comprehensive measures, it is difficult to make optimal organizational decisions at the supply chain level. Second, EA has not been fully utilized as a performance measure within the sustainable supply chain and CE contexts at the product level, which impacts the growth and understanding of this specific field of study (He et al., 2020; Panchal et al., 2021). The unique characteristics of EA as a sustainable supply chain performance measure presents rich opportunities to advance these sustainability-oriented fields. Third, the existing EA literature lacks an organizational theory-driven approach within a sustainable supply chain and CE context (Alkhuzaim et al., 2021). This gap hinders the integration of EA as an aggregate performance measure from a broader level of analysis into the granular level of SSCM. Opportunities for further investigation exist in addressing the many theoretical gaps that prevent the efficient application of emergy to supply chain management (SCM) and circularity research. Fourth, although SCM practices are strongly influenced by government policy and regulatory actions, the current literature overlooks the significance of such issues within supply chains, especially in the context of sustainability and CE (Fugate et al., 2019; Sembiring et al., 2020; Tokar and Swink, 2019). Therefore, the availability of emergy-based measurable indices of policy implications jointly advances the fields of EA, SCM, and SCM. This research provides a theory-based approach to help supply chain scholars and practitioners plan scientifically designed supply chain mitigation strategies, such as those related to sourcing (Talluri et al., 2013).

This research seeks to address the lack of a theory-driven approach, the limited application of EA at an organizational level, and the impact of government policy in a CE supply chain setting. These three overarching issues are at the heart of the two research questions that this dissertation thesis seeks to answer. The first question focuses on EA's capacity to be integrated into the supply chain level from the perspective of the natural resource dependence theory (NRDT) introduced by (Tashman, 2011). NRDT will be incorporated to narrow the focus of EA from a broad environmental level to a CE supply chain level. Then, the theory's two main elements will be evaluated using emergy-based indicators. The NRDT elements are: (1) ecological impact on organizations including dependency on natural resources, and (2) organizational impact in natural system and dependency on natural resources. The second question aims to test the impact of two policies using system dynamics (SD) modeling from the perspective of EA at the supply chain level.

These research questions are addressed by integrating emergy analysis into supply chain research and employing an organizational theory perspective. Part of this investigation is to help identify how emergy can work with policy making from a governmental focus. The poposed SD model acts as a policymaking tool which will focus on an actual supply chain—one that likely has CE and sustainability concerns. In this research, SD will be used as a policymaking tool to help evaluate the supply chain under study. The investigation will address some specific supply chain concerns to show how emergy can benefit SCM. Moreover, this research identifies policy implications of emergy measures at a circular supply chain level, all built on the premises of

NRDT. This evaluation will include a comparative analysis of emergy-based measures of two CE supply chain by-products under different policy intervention scenarios.

This dissertation thesis covers the aspects of supply chain evolution from a traditional organizational unit to a more strategic approach necessary for finding a balanced relationship between organizations and their environment. Chapters 2 and 3 cover the literature and theoretical background essential for a comprehensive investigation of the proposed methodology. Chapter 2 covers a multidisciplinary review of all related literature streams, including SCM, performance measures, CE, and EA. The theoretical foundations supporting this research, along with the research objectives and questions, are discussed in Chapter 3. Next, to help address the research objectives and questions, Chapter 4 provides an overview of the applied case study and introduces the process of data collection. Chapters 5 and 6 quantitatively assess the case study using EA and SD, respectively. Then, Chapter 7 presents a comprehensive representation of the results and related discussions. Finally, Chapter 8 provides a conclusion, including a summary of this dissertation thesis, limitations, and potential avenues for future research.

CHAPTER 2 : BACKGROUND AND LITERATURE REVIEW

The last decade has seen an increase in individual, organizational, and governmental awareness of sustainable practices, which has coalesced into a powerful force for change (Taticchi et al., 2015). Motivated by a newfound understanding of the importance of sustainable practices in improving quality of life for all supply chain stakeholders, researchers sought to develop specific performance measures for evaluating such practices.

The relationship between supply chains and the natural environment has long been evaluated from the user's perspective of a product's value (Odum, 1996), ignoring the effort made by nature to produce various kinds of resources (Tian and Sarkis, 2020). The interplay between the natural environment and supply chains becomes more pivotal as supply chains continue to evolve and grow more complex; therefore, the need to expand evaluation measures to manage such interrelations is also growing (Fahimnia et al., 2015; Fritz et al., 2017; Jabbour et al., 2020; Tachizawa and Wong, 2015). Emergy analysis (EA) gives different evaluation insights into the performance of supply chains by incorporating donor-side valuation, thus giving more weight to nature's contribution to human-dominated production systems (Odum, 1996).

To investigate the system under study, this research builds on the current literature to test the feasibility of integrating supply chain management (SCM) and EA. Thus, this chapter contains the following sections, covering several literature streams, including SCM, circular economy (CE), performance measures and EA, in Sections 2.1, 2.2, 2.3, and 2.4, respectively. Then, the review methodology for the selected emergy literature employed in this dissertation is presented later in this chapter in Section 2.5.

2.1 Supply Chain Management

Over the past several decades, SCM has grown exponentially and diversified to address various realms. SCM is an integral part of the any organization because it acts as a bridge between the focal organization and the parties comprising the supply chain. Thus, major part of organizational success is associated with efficient and effective management of the supply chain.

Originating in the early 1980s, SCM is responsible for managing material and information flows to produce a product or provide a service by organizing a series of activities linking up- and downstream parties within the supply chain (Lambert, 2008, p. 2). As supply chains evolve over time, more functions and disciplines are added within the SCM umbrella. A more recent definition by the Council of Supply Chain Management Professionals (CSCMP) states that SCM includes the planning and management of all operations related to sourcing and procurement, conversion, and logistics. Moreover, coordination and collaboration with channel partners, such as suppliers, intermediaries, third-party service providers, and consumers, are essential SCM activities (Vitasek, 2013). To further simplify the definition of supply chain, it is important to identify the main players in the value chain, typically consisting of multiple firms and final users.

One of the most recent definitions, by Min et al. (2019), describes SCM from a more strategic point of view. Their definition emphases the importance of the strategic coordination of organizational functions in improving the long-term performance of the focal firm in general and the supply chain in particular.

2.1.1 Sustainable Supply Chain Management

As the consumption of natural resources increases, the world faces threats of scarcity and growing pollution by emissions. Thus, production and consumptions systems—including the supply chain—require reconsideration in this environment, or at least careful monitoring. The supply chain and SCM necessitates consideration of multiple stakeholders in the value chain, both inside and outside the boundaries of the focal firm. The growing complexity of supply chains operations and functions is sometimes the cause of internal (e.g., employees) and external (e.g., government, NGOs and society) stakeholder pressures that may drive substantial supply chain transitions (Johnstone, 2020).

The concept of sustainable supply chain management (SSCM) evolved in response to these challenges. SSCM seeks to capture all the activities performed within the supply chain to improve not only the economic performance but also environmental and social performance (Bai and Sarkis, 2010; Carter and Rogers, 2008). This has been defined as the "triple bottom line" (3BL) (Elkington and Rowlands, 1999).

The most common definition of sustainability describes it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987, p. 8). This definition can be viewed as the intergenerational philosophy of sustainability. There is also the 3BL definition. Expanding both of these concepts to the supply chain results in SSCM (Seuring and Müller, 2008).

Integrating sustainability practices into the supply chain has become a priority in its design and execution. The aim is to achieve superior economic performance while meeting environmentally conscious market and stakeholder requirements. Socially, the goal is to also maintain high social and ethical standards.

In theory, sustainability requires the reconciliation of the 3BL dimensions. Studies within the SSCM literature provide a wide overview of related and various topics. However, the economic dimension has always been the primary focus of researchers, who consider the attractiveness of the financial gains reaped by incorporating sustainability practices into the supply chain.

Alternatively, social issues remain underrepresented due to difficulties associated with defining and molding the social aspects of sustainability (Dempsey et al., 2011; Seuring, 2013). For instance, the initial goal for firms seeking sustainability is cost reduction, which has been the dominant criteria for the economic dimension (Seuring, 2013). Furthermore, a review conducted between 2000 and 2015 revealed that the economic dimension remains predominant in SSCM literature (Rajeev et al., 2017).

Economic and environmental dimensions are more frequently integrated within SSCM and green supply chain management (GSCM) literature. Many studies have focused on assessing the sustainable performance (economic and environmental) of specific industries, especially those with intensive energy consumption. Logistics operations are an example of highly polluting industries when incorporated with unsustainable practices and underdeveloped infrastructure (Khan, 2019). In this regard, Yu et al. (2018) tested the relationship between environmental and economic sustainability and green logistics performance. They found a strong positive correlation between green logistics and eco-friendly practices e.g., green energy sources). While greenhouse gas emissions and carbon emissions are negatively correlated with green logistics.

For the successful implementation of sustainable practices, the three pillars of sustainability (environmental, economic, and social) should be integrated to maintain long-term sustainable performance (Ahi and Searcy, 2013). EA may help integrate each of the three elements to one degree or another (Grönlund and Fröling, 2016); however, it is most effective for environmental resource management. Although supply chain sustainability performance has grown in importance since its broad introduction into the literature approximately 15 years ago (Hervani et al., 2005), substantially more work and development are needed.

2.1.2 Green Supply Chain Management

Integration between the concepts of sustainability and supply chain management, as well as the growing attention being paid to the environmental impacts of supply chain-related operations, led to the development of emergent fields such as GSCM (Ahi and Searcy, 2013). There is no consensus definition of the concept of GSCM; it has been defined by many scholars since its introduction in the mid-1990s (Fahimnia et al., 2015). Handfield et al. (1997) proposed one of the very first definitions of GSCM when they examined environmental management applications across the whole customer order cycle. Also, more recently, Büyüközkan and Çifçi (2012) defined GSCM as a way to increase ecological efficiency by decreasing environmental impact to achieve organizational goals.

2.2 Circular Economy

The concept of CE has also grown in importance to address various global economic and environmental concerns. Many CE models are related to waste effluents with a focus on improving the efficiency of used resources to achieve better economic performance (Ghisellini et al., 2016). As a business model, CE keeps materials and components within a closed loop to help organizations achieve the highest utilization of those resources (Webster, 2017). The primary goal of CE is to maximize environmental and economic benefits by reusing waste to produce new products. Also, ultimately, CE plays a role in improving overall environmental performance and human well-being (Murray et al., 2017).

The intersection between the bodies of literature on sustainability, SCM, and CE has yielded important findings and provides fertile ground for future research (Cooper et al., 2017; Corona et al., 2019; Genovese et al., 2017; Jia et al., 2020). Specifically, GSCM and CE are built around similar paradigms, both theoretically and practically (J. Liu et al., 2018). Circular activities can be implemented to improve performance at different levels of analysis, starting from the organizational level through eco-design and cleaner production initiatives, to the industrial level by advancing regional sustainability, and finally to the macro level through environmental initiatives to establish eco-cities (Murray et al., 2017).

The reverse supply chain is one of the most widely investigated applications of CE at the supply chain and organizational levels where practices such as recycling, reusing, and remanufacturing occur (Nasir et al., 2017). These CE practices are designed to reuse end-of-life materials and waste to produce new components (by-products) to maximize environmental and economic benefits (Di Vaio et al., 2023). Building on the same level of analysis, this dissertation research investigates the application of circular activities focusing on a particular by-product. More specifically, CE activities will be addressed from an ecological point of view, assuming that the plant is a closed system where depletion of natural resources equals the amount of waste generation (Genovese et al., 2017).

The integration of SSCM and the concept of CE provide a fruitful research area that must be explored. EA can help. Researchers have been urged to widen the scope of studies addressing the different angles of TBL dimensions by integrating multiple dimensions. This section further introduces possible integrations of SSCM, CE, and EA while focusing on the performance-measure aspects of sustainability in supply chains.

Considering the all-encompassing properties of EA, which is able to deal with both upstream and downstream activities, it is well suited to be a performance measure for circular activities. EA is capable of capturing supply chain activities, from the resource generation phase to the final product or service phase (Geng et al., 2013).

EA and CE integration has been addressed with a broad focus on SCM literature and more generic approach. Studies have integrated EA and other methods to conduct performance assessments at the industry level (Jamali-Zghal et al., 2015), industrial park level (Geng et al., 2010; Pan et al., 2016; Ren et al., 2010), and urban level (Santagata et al., 2020) for evaluating circular activities.

The literature shows that emergy and CE have been integrated mostly at the macro level (i.e., national, regional, city or municipal) to assess the sustainability of a particular region (Liu, et al., 2018). Also, Ren et al. (2010) used EA as an environmental strategy to evaluate the circularity of five scenarios in the Chinese paper industry, incorporating the social-economic-natural complex ecosystem theory (SENCE). Using emergy-based indices, they found that the adoption of CE policies in the Chinese paper industry requires “a scientific technical” structure and specific economic gains. Similarly, Santagata et al. (2020) applied EA at an urban level to determine the feasibility of such an application for circular strategies while comparing the performance of linear and circular systems.

2.3 Sustainable Supply Chain and Circular Economy Performance Measurement

Performance measures are frequently defined as methods of quantifying the efficiency and effectiveness of actions (Bai et al., 2019; Kazancoglu et al., 2018; Neely et al., 1995). In general, organizations have adopted and developed performance measures in order to manage their activities, programs, processes, and strategies. Performance measures that can evaluate the efficiency and effectiveness of supply chains are one such example.

The SSCM field experienced an evolution in performance measures that have been revised to cope with the increasingly competitive environment. Decision-makers are pressured to proactively manage the changes in the business environment, which requires comprehensive evaluation of a firm's performance (Nudurupati et al., 2011). It is essential to note the importance of using multidimensional performance measures that are able to assess both financial and non-financial performance for continuous sustainable improvement (Taticchi et al., 2015).

Within the context of SSCM, the literature on performance measures distinguishes between two main types: traditional (conventional) and contemporary (balanced) performance measures (Schaltegger and Burritt, 2014). Because traditional measures such as ROI and gross margin (Kaplan and Norton, 2005; Van Hoek, 1998) focus solely on the financial performance, their effectiveness for assessing general sustainability is questionable. Many researchers have argued that the limitations of traditional measures hinder potential growth and have therefore called for the use of more balanced performance measures (Ghalayini and Noble, 1996; Johnson and Kaplan, 1987). Alternatively, contemporary (balanced) performance measures focus on both financial and non-financial measures, which is more apt in assessing the various aspects of supply chains (Kaplan and Norton, 2005).

Recently, studies have integrated more innovative approaches for measuring the sustainability of supply chains by incorporating the 3BL pillars of sustainability (economic, social and environment) as the main assessment indicators. However, studies that have simultaneously integrated all three pillars remain scarce (Taticchi et al., 2015).

Some performance measures have been revised to address a specific dimension, as in the case of using Life Cycle Assessment (LCA) (Alcamo and Henrichs, 2002) to evaluate the corporate environmental performance (Gold et al., 2010). The supply chain operations reference (SCOR) model is another measure; it is used as an economically oriented strategic decision-making tool to assess supply chain performance based on four business processes: plan, source, make, and deliver (Bai and Sarkis, 2014).

Although existing performance measures have fundamentally contributed to the advancement of the SSCM field and the improvement of corporate sustainability, the need for innovative and comprehensive measures continues to grow. Also, given the relatively complex set of potential measures that are available, a metric that can bring together the various dimensions of sustainability—one that can incorporate social, economic, and environmental systems—may prove highly valuable. This is where EA can show its true worth. An in-depth look at how EA is employed will be provided in Sections 5.1, 5.2, 5.3, 5.4, and 5.5 of Chapter 5.

Environmental performance measures within the supply chain are concerned with the ecological impact of all the activities and processes performed along the supply chain to produce a product or provide a service (Shokravi and Kurnia, 2014). In addition, processes that occur throughout supply chain closed-loop activities can also have a critical environmental impact (e.g., as climate change and greenhouse gas (GHG) emissions) (Nidhi and Pillai, 2019). In fact, each function of the supply chain could have a distinct environmental effect that would eventually require unique measures to track its performance (McIntyre et al., 1998). As a result, organizations make every effort (and these efforts may vary depending on the environmental issue facing the supply chain stage) to adopt environmentally friendly practices within the supply chain to efficiently exploit their resources and minimize disruptive ecological impacts (Pagell and Gobeli, 2009).

With respect to the operational side of organizations, many factors have contributed to the growing need for developed environmental performance measures. One important aspect is the increasing complexity of operations and processes, which has complicated SCM using either outdated or one-dimensional performance measures (Dey et al., 2021). Another key player is the expansion of the competition environment from competition among organizations as whole entities to supply chain competition (Bai et al., 2012). According to Mollenkopf et al. (2010), environmental performance measures are widely addressed within GSCM literature; however, most of these measures are limited to the national supply chain scale. In the global supply chain context, organizations use International Organization for Standardization (ISO) certificates, such as ISO 14000 and ISO 14001, as standardized metrics to maintain a certain environmental footprint.

Despite the richness of literature within a broad context of supply chain and performance measures, some SSCM dimensions remain under-investigated (for example, the social dimension). Some researchers aim to create comprehensive performance measures by either developing multidimensional performance measures frameworks or revising the current performance measures to reflect all sustainability dimensions (i.e., economic, social, and environmental) (Agyabeng-Mensah et al., 2020; Taghipour and Beneteau-Piet, 2020). With regard to the environmental dimension, and because organizations can negatively affect the surrounding environment in multiple ways, there is a gap in the literature that must be filled by more inclusive measurements to track environmental performance (Middleton, 2015).

The supply chain operations reference (SCOR) model, developed by the Supply Chain Council (1999), is a tool designed to address economic-oriented strategic decision-making issues that are used to evaluate supply chain performance with respect to its four business processes (plan, source, make, and deliver) (Bai and Sarkis, 2014). By incorporating environmental performance, Bai et al. (2012) expanded the SCOR model to conduct a more holistic evaluation of the supply chain. Moreover, environmental performance measures in some techniques rely on expressing current performance in the form of incurred cost-equivalent measures (Bai and Sarkis, 2014). For example, life cycle costing assessment (LCCA) is used as a decision-making tool that expresses environmental issues in monetary terms by evaluating products' and services' life cycle costs in terms of their environmental consequences (Bennett and James, 1997; Gluch and Baumann, 2004).

The environmental challenges facing supply chains can encompass different levels of analysis, including local, regional, and global boundaries (Acquaye et al., 2017; Bai and Sarkis, 2014). Thus, environmental performance measures within SSCM must include multiple scales to improve not only organizational sustainability but also whole supply chains or industries. GHG emission is an example of a measurable indicator to assess environmental performance. As part of supply chain operations, GHGs are emitted during the production and transportation phase, which increases the environmental distress on the ecosystem and places serious pressure on the supply chain. According to the US Environmental Protection Agency, the industry sector was responsible for 22% of GHG emissions in 2017. Accordingly, measuring the GHG emissions (also referred to as "product carbon footprint") (Jensen, 2012) of supply chains is important environmental performance measure at both the organizational and industry levels.

From a life cycle perspective, researchers measured the carbon footprint to evaluate the environmental impact in a product's life cycle (Laurent et al., 2010). Another frequently used environmental tool is the LCA (Alcamo and Henrichs) modified to address a specific SSCM dimension to evaluate the corporate environmental performance (Gold et al., 2010). LCA is known to be a "standardized" measure and is most often used as a SSCM tool to mitigate environmental impacts caused during product and/or process life cycles (Lundin and Morrison, 2002). Compared to the carbon footprint, LCA is a more comprehensive approach in the sense that it includes all environmental impacts associated with the product life cycle, not exclusive to causes of climate change (Laurent et al., 2010). Predominantly, LCA has been integrated with other tools such as system dynamics (SD) and EA (Gala et al., 2015; Onat et al., 2016) to facilitate a more comprehensive evaluation of the system under study.

Environmental performance measures aim to provide researchers and decision-makers in the supply chain with dynamic tools to manage serious environmental concerns impacting the ecosystem, such as water and energy use, land footprint, waste generation and toxic release, and food security (Ardito and Dangelico, 2018).

Food and agriculture industries are known to be at the top of environmentally contributing sectors in terms of their harmful impact (Park et al., 2016). Intensive operations are associated with food and agriculture production processes, starting from raw material extraction to their transformation into products, consuming intensive renewable and non-renewable resources (Kucukvar and Samadi, 2015). Considering that food and agricultural activities are among the leading causes of environmental deterioration across the world (Poore and Nemecek, 2018), it is particularly critical to develop comprehensive performance measures capable of capturing the complexities of such operations. This is one of the gaps this dissertation thesis seeks to address.

Traditional measures of environmental performance, like LCA and carbon footprint, are designed to capture the performance of a particular system from the perspective of its user. In other words, Odum (1996) states that the real value of a user-driven system is determined based on how much the user is willing to pay, whereas a donor-side system is valued based on what was required to produce a certain product or service.

In summary, based on the current body of literature on sustainable performance measures, a majority of environmental performance measures focus on evaluations from the user side, thus ignoring the contribution of the donor side (nature). Nature's contribution represents the cornerstone of any economic or human-dominated system (Odum, 1988). Consequently, more investigation is needed to raise the profile of donor-side evaluation (Karuppiah et al., 2022). The next section reviews the concept of donor-side evaluation in detail.

2.4 Emergy Analysis

EA is one of the emerging performance assessment tools gaining increasing attention in the general ecological indicators research community (Karuppiah et al., 2022). Introduced by Odum (1996) as a thermodynamics and general systems theory, EA is an assessment tool that quantifies the accumulative available energy consumed directly or indirectly to produce a product or a service. It can be useful in providing a comprehensive evaluation of the environmental performance of the supply chain.

Unlike other environmental assessment tools and performance measures, EA quantitatively provides a real value for the work of nature—sun, wind, geothermal heat, and rain—in addition to that of humans in producing products and services. It considers the *donor* value of the environment into various commerce and society activities, and their systems (Odum, 1996). More specifically, the determining factor of an object's value derives from how much goes into it, rather than how much money it is worth (Brown and Herendeen, 1996). For example, from the user side, a wood stove and a coal stove both require the same amount of energy; however, from a donor side, the work performed by nature to produce these two fuels is different and, thus, they have different emergies (Raugei et al., 2014).

EA overcomes the limitation of having different units and flows and transforms all the energy flows into solar emergy joules (sej) (Corcelli et al., 2018; Song et al., 2014). It uses solar energy as the unique measuring unit to normalize different inputs and outputs of materials, products, and services (Odum, 1996). EA provides decision-makers with various indicators to review any given system from multiple dimensions (Jiang et al., 2009). These emergy-based indicators are a set of metrics and ratios used to measure the environmental impact along the production process beginning from resource generation to finished product (Odum, 1988).

To aid in visualizing its mechanism, it is useful to think of emergy as *energy memory*. In other words, when evaluating a system using emergy, all values represent the "memory" of solar energy used to produce it (Brown and Herendeen, 1996). Odum (1996) defines the solar emergy consumed to produce one joule of a product or a service as "solar transformity." Solar transformity measures the intensity of the support provided by the natural system to the final product. It is also considered as an indirect measure of "product renewability" and acts as a memory of past environmental contributions to the production of the final product (Brown and Ulgiati, 1997).

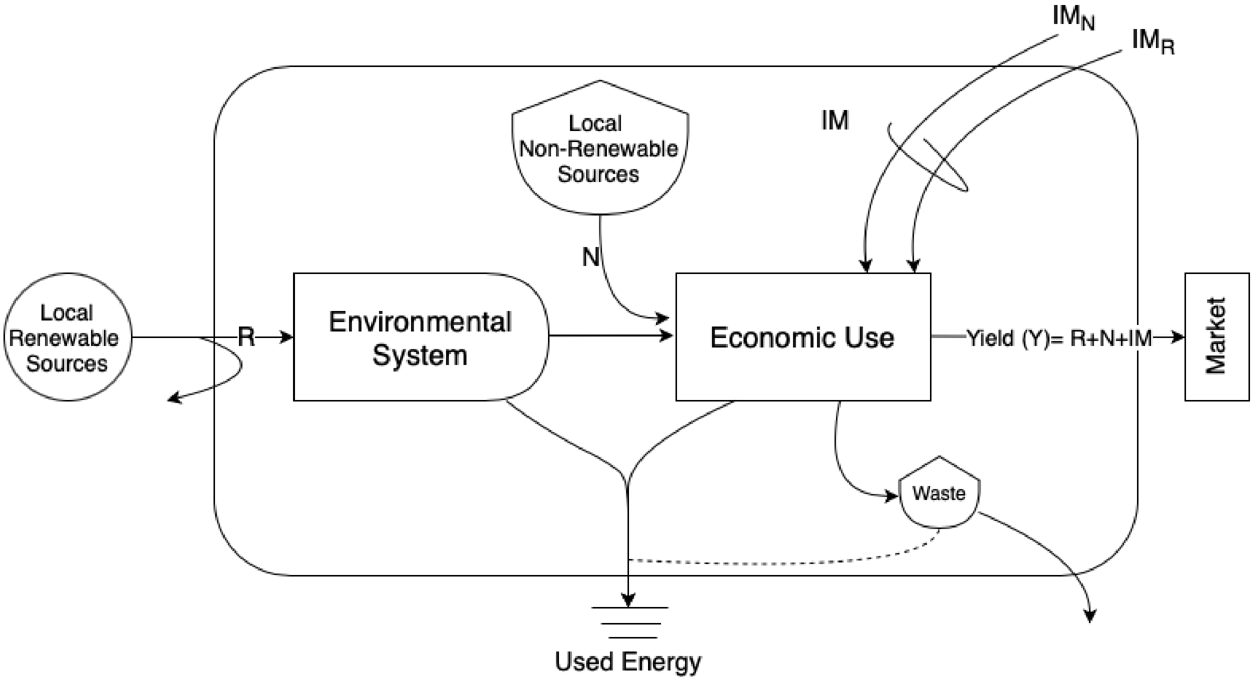
Transformities are also called unit emergy values (UEV), which represent intensity coefficients and are determined by dividing the system's total emergy (U) by the system's yield (Y): $UEV = U/Y$. Y represents the system's output in a product or a services form (Ulgiati and Brown, 2014). Higher transformity means that more energy and environmental activities are needed to produce a resource. Transformities are calculated by dividing the total emergy by the actual available energy used in the system under study. In fact, transformities are essential in quantifying the total emergy through multiplying transformity by the available energy.

Total emergy is the sum of all energy flows contributing to the production of a product or a service. In terms of units, the total emergy is measured in solar emergy joules (sej), whereas transformities are measured in solar emergy joules per joule of product (sej/J) (Brown and Ulgiati, 1997). Another important measure is the specific emergy, where the sum of all emergy flows is divided by the output unit mass and is expressed in solar emergy joules per gram (sej/gram)

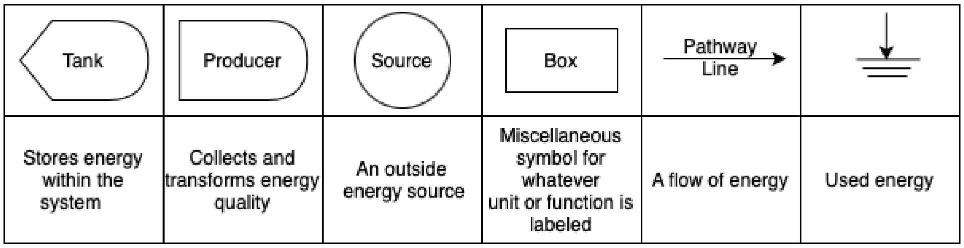
(Odum, 1996). According to Odum (1996), a high specific emergy ratio may indicate that the evaluated process, product, or service requires high environmental contribution. It could also indicate that the emergy required to produce a certain output is not proportional to its unit mass, which may imply a potentially low output in terms of dry mass.

EA can be illustrated by diagrams to depict the system under study in terms of all forms of energy consumed during the production of the final product or service (Figure 2-1). An emergy diagram contains symbols of sources, flows, storages, interactions and transactions (Brown, 2004). All these components are positioned within a closed system boundary to show how energy, materials, and information interact.

An example of an emergy diagram is shown in Figure 2-1, which illustrates the main components of a system under study. It contains flows of input and output accounting for local renewable sources (R), local non-renewable sources (N) and imported (purchased) resources from outside the system. The diagram also identifies interactions between system's components up until the production of the final product. Used energy represents the energy that is no longer capable of providing work to the system and thus sinks through the bottom pathway as heat (Odum, 1996). Descriptions of the emergy symbols and notations are in Figure 2-1.



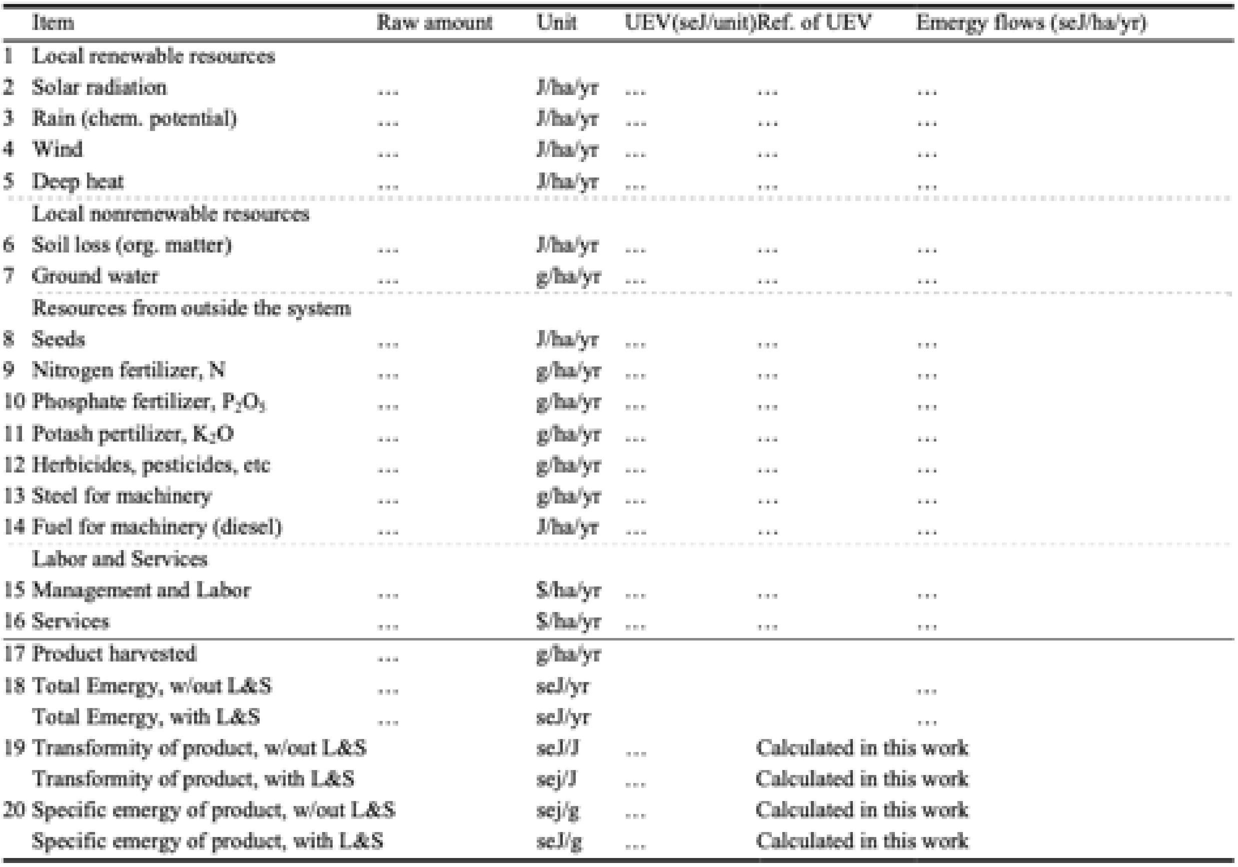
Note: Energy sources include (1) Local Renewable Sources (R) such as sun, wind, rain, and solar radiation; (2) Local Non-renewable Sources (N) such as groundwater and biomass and topsoil; (3) Imported (purchased) resources (IM) including renewable (IM_R) and non-renewable (IM_N) flows imported from outside the boundaries of the system of interest such as fuel, raw minerals, wood, machinery, and chemicals; (4) Direct labor (L) and indirect labor in the form of services (S); and (5) Waste (W); (6) Total emergy (U) (U= R+BN=IM); and (7) System's yield (Y) such as product, service, and emissions.



Tank	Producer	Source	Box	Pathway Line	
Stores energy within the system	Collects and transforms energy quality	An outside energy source	Miscellaneous symbol for whatever unit or function is labeled	A flow of energy	Used energy

Figure 2-1: Emergy System Diagram

Ulgiati and Brown (2014) provided a guideline for emergy calculations by providing a computational template table shown in Figure 2-2 for the raw sources, UEVs (transformities), and emergy flows. Because transformities are derived from the literature, some of these values need to be updated.



	Item	Raw amount	Unit	UEV(seJ/unit)	Ref. of UEV	Emergy flows (seJ/ha/yr)
1	Local renewable resources					
2	Solar radiation	...	J/ha/yr	...	...	...
3	Rain (chem. potential)	...	J/ha/yr	...	...	...
4	Wind	...	J/ha/yr	...	...	...
5	Deep heat	...	J/ha/yr	...	...	...
	Local nonrenewable resources					
6	Soil loss (org. matter)	...	J/ha/yr	...	...	...
7	Ground water	...	g/ha/yr	...	...	...
	Resources from outside the system					
8	Seeds	...	J/ha/yr	...	...	...
9	Nitrogen fertilizer, N	...	g/ha/yr	...	...	...
10	Phosphate fertilizer, P_2O_5	...	g/ha/yr	...	...	...
11	Potash pertilizer, K_2O	...	g/ha/yr	...	...	...
12	Herbicides, pesticides, etc	...	g/ha/yr	...	...	...
13	Steel for machinery	...	g/ha/yr	...	...	...
14	Fuel for machinery (diesel)	...	J/ha/yr	...	...	...
	Labor and Services					
15	Management and Labor	...	$/ha/yr	...	...	...
16	Services	...	$/ha/yr	...	...	...
17	Product harvested	...	g/ha/yr			
18	Total Emergy, w/out L&S	...	seJ/yr			...
	Total Emergy, with L&S	...	seJ/yr			...
19	Transformity of product, w/out L&S		seJ/J	...	Calculated in this work	
	Transformity of product, with L&S		sej/J	...	Calculated in this work	
20	Specific emergy of product, w/out L&S		sej/g	...	Calculated in this work	
	Specific emergy of product, with L&S		seJ/g	...	Calculated in this work	

Note: J: Joules, ha: Hecate, yr: Year, g: gram, seJ: Solar emjoule.

Figure 2-2: Emergy Template Table

After calculating the total emergy of the flows feeding the system under study, emergy-based indicators are used to measure the environmental and sustainability performance of the system of interest. Furthermore, emergy-based indicators are important inputs to support policymaking processes because they describe the dynamics of the system of interest. Emergy provides a wide set of indicators that researchers and policymakers can choose from, depending on their ultimate goal. Emergy loading ratio (ELR) measures the amount of environmental burden caused by production processes; it is calculated as the ratio of the sum of local non-renewable resources (N) and imported emergy (IM) to the renewable resources (R): $[(N+IM)/R]$ (Ulgiati et al., 1994). A high ELR indicates high environmental pressure and is a sign of harmful environmental practices.

The emergy yield ratio (EYR) is an indicator of the ability of a process to make use of local resources by investing in non-local resources. It provides an understanding of the support that a process can offer to the local economy by exploiting local resources. EYR is calculated by dividing the sum of all resources used in the production (renewable, non-renewable, and imported) to the imported emergy: $[(R+N+IM)/IM]$. An effective system makes greater use of the available local resources while importing less emergy from the economy (Odum, 1996). Therefore, the greater the EYR, the better.

The emergy investment ratio (EIR) is a measure of the "utilization level" of the used emergy (Ren et al., 2015). It indicates whether a process is effectively using the invested emergy. It is the ratio of the imported emergy (IM) (renewable and non-renewable) to the natural inputs ($R+N$): $[(IM/(R+N)]$. EIR is the ratio of purchased energy to free emergy (Odum, 1996).

The emergy sustainability index (ESI) (Dey et al.) is a measure of the sustainability of a process, product, or service. ESI is considered an aggregate measure because it is the ratio of the contribution of a process to the local economy (EYR) to the amount of its emergy loading (ELR):

(EYR/ELR). Brown and Ulgiati (2002) provided a reference for ESI to evaluate the sustainability level of a particular process or product as follows:

- $ESI < 1$ ➔ represents a non-sustainable process (product) in the long term with high environmental pressure
- $ESI > 1$ ➔ represents a long-term sustainable process (product)
- $1 < ESI < 5$ ➔ represents a moderate level of sustainability

Percent renewable *(%R)* is another sustainability indicator that divides the renewable resources ($R + IM_R$) by the total emergy (U): $\%R = (R+IMR)/U$. Comparing multiple alternatives, a high percentage indicates a more sustainable system. Also, *%R* is an indicator of a system's ability to withstand economical pressure (Brown and Ulgiati, 2004; Cavalett et al., 2006).

Although EA is an environmental assessment tool, it provides a number of monetary measures from an ecological point of view. The emergy exchange ratio (EER) is the ratio of emergy embodied in the money invested to the embodied emergy of the sold product: $EER = [(\$_{income}) * (sej/\$)_{world}]/U$ (Asamoah et al., 2017). A value less than 1 indicates that the emergy of the product exceeds the emergy of the money. This begins to include economic valuation along with other sustainability measures. Table 2-1 below summarizes the most important notations and indicators of EA along with their definitions and formulas. Table 2-1 below summarizes the most important notations and indicators of EA along with their definitions and formulas.

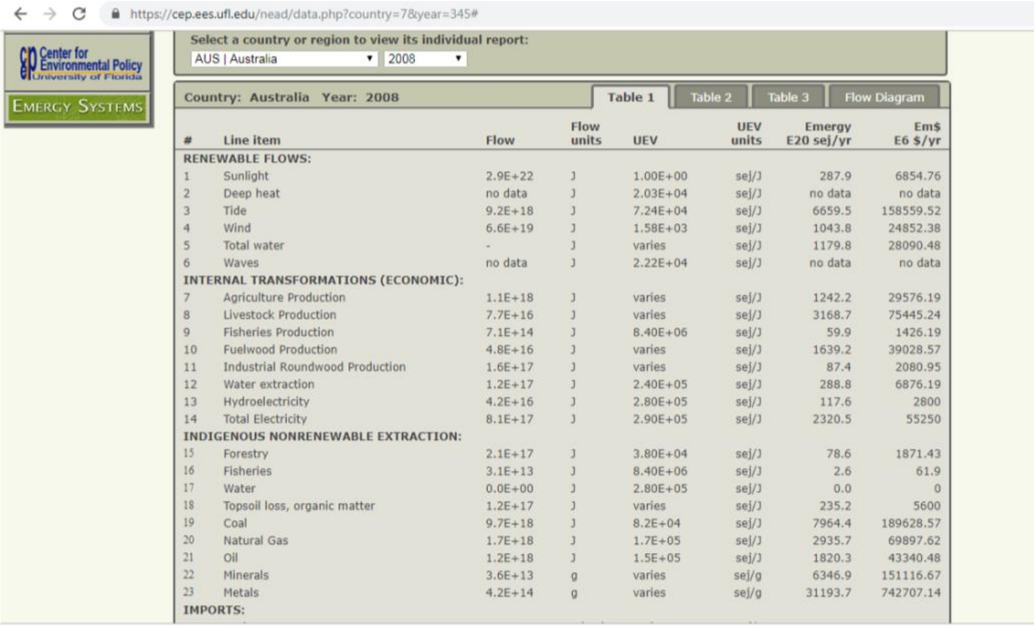
Table 2-1:Emergy Based Indicators

Index	Notation	Definition
Local Renewable Sources	R	Emergy of the renewable locally available sources, such as sun, wind, rain and solar radiation.
Local Non-renewable Sources	N	Emergy of local sources that are being consumed at a rate faster than they can be regenerated. These are ground water, biomass and topsoil, fossil fuels, and minerals.
Imported (purchased) Resources	IM (IM_R, IM_N)	Emergy of resources that have been purchased from outside the boundaries of the system of interest. They include renewable and non-renewable purchased raw and refined materials such as fuel, machinery, chemicals, and commodities.
Exported Resources	E	Emergy of the flows and resources leaving the system as inputs to the economy.
Labor	L	Emergy embodied in the human activities performed within the system's boundary.
Services	S	Emergy of activities taking place outside of the system's boundary to facilitate the delivery of imported resources.
Total Emergy	U = R+N+IM	Total emergy of the system of interest.
Emergy Loading Ratio	ELR = (N+IM)/R	Measure of the amount of environmental burden caused by production processes.
Emergyl Yield Ratio	EYR = (R+N+IM)/IM	Measure of the ability of a process to make use of local resources by investing in non-local resources.
Emergy Investment Ratio	EIR = IM/(R+N)	Measure of the "utilization level" of the used emergy.
Emergy Sustainability Index	ESI = EYR/ELR	Measure of the sustainability of a process, product, or service.
Percent Renewable	%R=(R+IMR)/U	A sustainability indicator that divides the renewable resources (R + IM_R) by the total emergy (U). It is also an indicator of system's ability to withstand economical pressure.

Emergy Exchange Ratio	EER= $[(\$_{income}) * (sej/\$)_{world}]/U$	The ratio of emergy embodied in the money invested to the embodied emergy of the sold product.

To create an EA evaluation system, three main phases must be completed (Tian and Sarkis, 2020). The first is to set the boundaries of the system under study in preparation for creating an emergy diagram. This phase includes determining primary components (i.e., material and energy flows) of the system along with their relationships. Second, input flows of the system (i.e., matter, energy and capital) are converted into solar equivalent values by multiplying each flow by a respective transformity (UEV). Moreover, the respective emergy values of labor and services require further analyses depending on the system's boundary (Ulgiati and Brown, 2014). Third, emergy indicators are calculated to finally evaluate the performance of the system under study and give a better understanding for proper environmental and economic assessment.

To be able to develop these various measures, an emergy database of values for global activities, systems, resources, and regions is publicly available from the National Environmental Accounting Database (NEAD) (Dempsey et al., 2011), which is used to inform various tables and calculations completed at the national level. The NEAD database, which is continuously updated, is available at: https://cep.ees.ufl.edu/nead/. Designed in 2003 and updated in 2014, the NEAD aims to help researchers and scholars advance emergy as a methodology and a theory by comparing emergy valuations and indicators over time (Viglia et al., 2018). An excerpted data set and screenshot of the site appears in Figure 2-3. This data is for Australia using the 2008 database. The data includes three detailed tables based online items with flows and scores. In many cases, a flow diagram is also part of the database.



Select a country or region to view its individual report:
AUS | Australia
2008

Country: Australia Year: 2008

#	Line item	Flow	Flow units	UEV	UEV units	Emergy E20 sej/yr	Em$ E6 $/yr
RENEWABLE FLOWS:							
1	Sunlight	2.9E+22	J	1.00E+00	sej/J	287.9	6854.76
2	Deep heat	no data	J	2.03E+04	sej/J	no data	no data
3	Tide	9.2E+18	J	7.24E+04	sej/J	6659.5	158559.52
4	Wind	6.6E+19	J	1.58E+03	sej/J	1043.8	24852.38
5	Total water	-	J	varies	sej/J	1179.8	28090.48
6	Waves	no data	J	2.22E+04	sej/J	no data	no data
INTERNAL TRANSFORMATIONS (ECONOMIC):							
7	Agriculture Production	1.1E+18	J	varies	sej/J	1242.2	29576.19
8	Livestock Production	7.7E+16	J	varies	sej/J	3168.7	75445.24
9	Fisheries Production	7.1E+14	J	8.40E+06	sej/J	59.9	1426.19
10	Fuelwood Production	4.8E+16	J	varies	sej/J	1639.2	39028.57
11	Industrial Roundwood Production	1.6E+17	J	varies	sej/J	87.4	2080.95
12	Water extraction	1.2E+17	J	2.40E+05	sej/J	288.8	6876.19
13	Hydroelectricity	4.2E+16	J	2.80E+05	sej/J	117.6	2800
14	Total Electricity	8.1E+17	J	2.90E+05	sej/J	2320.5	55250
INDIGENOUS NONRENEWABLE EXTRACTION:							
15	Forestry	2.1E+17	J	3.80E+04	sej/J	78.6	1871.43
16	Fisheries	3.1E+13	J	8.40E+06	sej/J	2.6	61.9
17	Water	0.0E+00	J	2.80E+05	sej/J	0.0	0
18	Topsoil loss, organic matter	1.2E+17	J	varies	sej/J	235.2	5600
19	Coal	9.7E+18	J	8.2E+04	sej/J	7964.4	189628.57
20	Natural Gas	1.7E+18	J	1.7E+05	sej/J	2935.7	69897.62
21	Oil	1.2E+18	J	1.5E+05	sej/J	1820.3	43340.48
22	Minerals	3.6E+13	g	varies	sej/g	6346.9	151116.67
23	Metals	4.2E+14	g	varies	sej/g	31193.7	742707.14
IMPORTS:							

Figure 2-3: An example set of emergy assessment data from the National Environmental Accounting Database located at the University of Florida

EA allows for a comprehensive environmental assessment from two different perspectives. First, by using emergy-based indicators, multiple alternatives can be evaluated based on the results obtained from calculating the appropriate emergy indicators. Then, the alternative with the least prominent results is eliminated (Corcelli et al., 2018). Alternatively, emergy-based indicators are useful as time assessment tools whereby indicators are measured over time to describe a certain pattern or identify key resources (Song et al., 2014). The first approach is for decision-making purposes and the alternative is for benchmarking; both can be used for planning and management purposes.

From an SSCM perspective, increasing consumption of non-renewable natural resources is a global challenge that aggravates scarcity issues. Despite recent initiatives to encourage the adoption of eco-friendly practices in manufacturing, resource overuse and waste generation remain serious industrial greening concerns. The main challenge is to increase the efficiency of used resources by maximizing their utilization rate to reduce waste as much as possible—or to shift toward renewable resources with lessened environmental degradation concerns.

2.5 Review Methodology

This section provides a comprehensive literature review of EA within the context of SSCM and the CE. The review process is based on the procedure of the preferred reporting items for systematic reviews and meta-analysis (PRISMA) developed by Moher et al. (2009). Using Google Scholar as the primary database, four keywords were searched: “emergy,” “circular economy,” “supply chain,” and “sustainability.” With no timeframe specification, the initial search yielded 271 publications, marking the year 2010 as the starting point for publications matching the used keyword criteria. Thus, the specific timeframe of the selected articles ranges from the 2010 to 2023. The review excluded non-English articles, books, publications from non-scientific journals, conference proceedings, and book chapters. Following that, the remaining 210 articles were thoroughly reviewed using content analysis. The search returned only 24 articles that met the used keyword criteria. Table 2-2 presents a literature summary of all the selected articles categorized across multiple level of analysis, highlighting the theoretical and methodological contribution of each study. A comprehensive analysis of the relevant literature is presented in the following section.

Table 2-2:Emergy Analysis Literature Summary

Papers	Level of Analysis	Theory	Methodology
(Brown et al., 2009)	National	--	--
(Ren et al., 2010)	Industrial Park/CE	SENCE	--
(Geng et al., 2010)	Industrial Park/CE	--	--
(Song et al., 2014)	Urban/Regional	--	SD
(Markussen et al., 2014)	Supply Chain	--	LCA
(Ren et al., 2015)	Supply Chain	LCP	LCA & MINLP
(Jamali-Zghal et al., 2015)	Industry/CE	--	LCA
(Park et al., 2016)	Industry	--	LCA
(Pan et al., 2016)	Industrial Park/CE	--	--
(Asamoah et al., 2017)	Supply Chain	--	--
(Fang et al., 2017)	Urban/ Regional	--	SD
(Huang et al., 2018)	Urban/ Regional	--	SD
(Xue et al., 2018)	Urban/ Regional	--	SD
(Corcelli et al., 2018)	Supply Chain	--	--
(Pan et al., 2019)	Industry	--	--
(Tian and Sarkis, 2020)	Supply Chain	--	--
(Krishnan et al., 2020)	Supply Chain	--	LCA
(Wu et al., 2020)	Urban/ Regional	--	GTAP
(Ekinci et al., 2020)	Industry	--	SD
(Wu et al., 2021)	Industry	--	SD
(Chen and Liu, 2022)	Industry	--	--
(Huo et al., 2022)	Urban/ Regional	--	SD
(Zhao et al., 2022)	Industrial Park	--	SD
(Sun et al., 2023)	Industry	--	LCA

The current literature combining EA and SCM shows a variation in the distribution of published articles based on the level of analysis. A large body of literature is focused on the macro level of analysis (i.e., national, regional, city or municipal) when evaluating supply chain-related issues and performance. Few studies have targeted the more narrow scope of the supply chain with an operational and managerial focus (Tian and Sarkis, 2020).

EA is affected by data availability, which makes it easier to apply in a broad level of analysis (e.g., national and regional) (Tian and Sarkis, 2020). A number of studies have covered the macro level, assessing the sustainability of regions and cities (Brown et al., 2009; Huo et al., 2022; Lou and Ulgiati, 2013; Wu et al., 2020). Also, Geng et al. (2010) used EA to evaluate the eco-efficiency of Dalian Economic Development Zone (DEDZ) in China as a case study focusing on the industrial park level. They used emergy-based indicators, (i.e., ELR and EYR) to evaluate the current development situations of the DEDZ. The results offered new ventures for sustainable development through recycling and byproduct initiatives to help stakeholders and administrators in the decision-making process.

Few generic supply chain studies are found in the literature. These studies, however, are conceptually presented EA as a methodology without a clear comparison of alternative products, implications for organizational and supply chain decisions, or integration of a real-world case study targeting supply chains. For instance, Corcelli et al. (2018) used EA to assess the effectiveness, efficiency, and sustainability of papermaking processes, starting from virgin pulp (upstream) to the final product, paper (downstream); their study used a generic application of the integration between EA at the supply chain level. They used emergy-based indicators to evaluate the sustainability of three different forest management scenarios—eucalyptus, spruce/pine, and poplar—as the sources for raw material supply in three regions: Sweden, Italy, and Brazil. They compared the amount of energy and past environmental activities (transformities) consumed in the three tree species, finding that spruce/pine was the most sustainable option because it required the lowest transformations.

Another generic application of EA to the supply chain integrated EA with LCA to evaluate two generic food supply chains in the UK (Markussen et al., 2014). Furthermore, a more recent study presented a conceptual model of emergy within the food supply chain (Krishnan et al., 2020), assessing a mango food supply chain from an LCA perspective to detect inefficiencies related to operational and resource use. Krishnan et al.'s methodology helped redesign the food supply chain to achieve more environmentally sustainable performance.

The use of EA complements the results obtained with other environmental performance systems. Some studies integrated EA with LCA to measure systems. For instance, Ren et al. (2015) used emergy-based indices to measure the sustainability of a biodiesel supply network by taking a life cycle perspective (LCP) to evaluate multiple designs of the biodiesel supply network. A mixed-integer non-linear programming (MINLP) model was also used. This study provided a generic model to strategically design the supply chain.

Although EA has not yet been intensively applied at the supply chain level of analysis, some studies have shown significant results. For example, Cai et al. (2020) built an emergy model to investigate the sustainability of outsourced machining resources to support more efficient resource consumption. They created several emergy models: production quality emergy, production time emergy, production logistics cost emergy, and production resources consumption emergy. Their results supported the feasibility of EA in outsourcing machining resources. Also, a study by Tian and Sarkis (2020) focused conceptually on the feasibility of using EA at the supply chain level to evaluate supplier selection options as an example. Their study provided a conceptual perspective for applying EA at the supply chain level in general and green supply chain management in specific.

From a broader level of analysis, EA has been applied at the industry level. For instance, Yang et al. (2003) applied EA in the coal industry with a focus on waste management. Pan et al. (2019) applied EA to the lead-acid battery industry in China while investigating recycling systems of a firm in Yunnan using emergy-based indicators. Their results showed that the system investigated was intensively dependent on non-renewable resources despite showing some significant recycling efficiencies. Another industry-level application is found in (Jamali-Zghal et al., 2013), who conducted a comparative study to substitute wood for natural gas to achieve cleaner heat production in Nantes, France. Their study aimed to evaluate the sustainability and eco-efficiency of using biomass instead of fossil fuels for heat production, using emergy and carbon footprint as performance measures. This example shows how current studies adopt a more environmental approach to production systems rather than evaluating supply chain decisions from a narrower perspective.

Integrations between SD and EA have tended to be applied within a broader level. For instance, SD has been integrated as a policy testing tool to evaluate emergy systems at an urban metabolic level (Fang et al., 2017; Huang et al., 2018; Huo et al., 2022; Liu et al., 2014; Song et al., 2014; Xue et al., 2018), industrial park level (Zhao et al., 2022), and industry level (Ekinci et al., 2020; Liu et al., 2014; Wu et al., 2021). For the most part, the focus of these published studies was at a macroscopic level, with very few narrowly focused studies.

Overall, most of the studies that integrated EA into the supply chain level provide a generic perspective of emergy applications in the supply chain with no focus on a particular product or specific supply chain (Tian and Sarkis, 2020). Theoretical frameworks are also absent from the current literature linking EA with supply chain-level issues. Additionally, the use of emergy versus other performance measures for all the published work is driven mainly by its ability to provide a donor-side measure for nature’s contribution to the economic system (Tian and Sarkis, 2020). Contrarily, other performance assessment tools give a user-side measure to systems under study. For example, from the user side, a wood stove and a coal stove both require the same amount of energy; however, from the donor side, the work done by nature to produce these two fuels is different; thus, they have different emergies (Raugei et al., 2014).

EA can directly differentiate between products originated from linear and non-linear supply chains using emergy-based indicators (Marvuglia et al., 2018). Also, when evaluating the supply chain, information is an important flow that can determine the level of circularity, which EA is designed to account for and measure. EA can also help in identifying flows within and between organizational activities, although this use has not yet been extensively studied.

Another advantage of EA is derived from its encompassing nature. EA has been successful in measuring regional sustainability within a specific geographical boundary. In reality, businesses operating in a developed region achieved better performance when adopting sustainable and green practices, whereas in developing regions, circumstances are not always ideal to reward such practices. With more limited capabilities and less stringent regulations, developing regions tend to overuse their natural resources in unsustainable approaches to achieve rapid economic growth, which will eventually aggravate serious environmental concerns (Khan, 2019; Khan et al., 2017b). In a study conducted to evaluate the environmental and economic performance of a Pakistani firm, it was found that although green practices had a positive impact on environmental performance, economic performance did not improve (Khan and Qianli, 2017). Thus, using EA as a tool along with other performance measures can significantly widen the evaluation scope by accounting for the environmental contribution of any particular region to give a better assessment of the current situation.

Unlike other environmental assessment tools and performance measures, EA can quantify the work of nature and assign real values to facilitate a more objective performance assessment (Tian and Sarkis, 2020). In general, other performance measures account for the effect of some environmental practices (e.g., quantity of CO_2 emissions) and overlook the real ecological contribution to produce a product or a service.

An essential feature of EA that differentiates it from other performance measures is its ability to account for different flows with different units and integrate them into one measurable unit, the solar emergy joule (sej). It integrates natural resources, purchased resources, human contribution, and information (Brown and Buranakarn, 2003). EA is considered one of the most comprehensive tools in measuring the TBL dimensions, including social, labor, and economic concerns (Alkhuzaim et al., 2021).

Similar to other performance measures, EA has some limitations that must be improved and revised. Deriving from thermodynamics and general systems theory, EA can be integrated more interactively with other fields to advance its applications. However, the biggest limitation is the underdeveloped state of the literature connecting EA to other disciplines such as SSCM. Much of the data is at a very fine level of granularity.

The applications of EA as a performance measure can be advanced by targeting different levels of analyses. Disaggregating this data to the organizational, product, or supply chain level takes careful thought and examination, and the sourcing of materials becomes a major issue. In this case, the regional origins of various components in a material or product are difficult to identify. Calculating the basic effort in value adding processes and the source location of materials is sometimes challenging.

EA also requires a set of numeric calculations and specific parameters that may be either unavailable or outdated in some regions. In developing countries where significant basic resources are extracted, data availability is often poor (Amaral et al., 2016). This limits the results obtained by EA and emergy-based indicators.

Given the complex nature of EA, large-scale production systems (i.e., at the regional level) can be quite different. These broader levels are used to evaluate the environmental performance, which raises potential uncertainties of EA's ability to evaluate small-scale production systems (Asamoah et al., 2017).

Another downside of using EA is the level of complexity associated with communicating and explaining the logic behind it. Because EA extends to the level of resource formation—far beneath the apparent typical production system—it is not easy to rationalize system boundaries and results obtained by using emergy-based indicators, which may also be subject to different interpretations (Raugei et al., 2014).

EA also faces obstacles to applications in business, where traditional performance measurement systems are already in place; significant effort would be required to adjust these systems for EA. For example, bills-of-material are used to manage many products through enterprise resource planning systems; determining how to link these systems and their data to EA would be a highly complex challenge. Developing the linkages and databases is a major concern, but new technologies such as blockchain technology (Kouhizadeh and Sarkis, 2018) may be useful in this situation as emergy data becomes updated.

Furthermore, it is not clear how the data would account for evaluations of categories such as equipment. First, calculations of emergy values is not highly transparent; such data would need to be made more transparent to reveal underlying assumptions and sources. Second, given that components such as equipment are based on resources and energy used to calculate their emergy, how are the values allocated? For example, a piece of factory equipment might manufacture millions of products over its lifetime. The unit of analysis would be necessary information. Also, because a major portion of equipment may be resold or reused, how this end-of-life emergy is assigned also becomes an issue.

Decomposition of emergy information to the factory and product level over the life of an operation, as well as its after-life, must be carefully planned. It will likely be based on future forecasts of the life of the product, as well as on how many times and in how many ways the material is recycled or reused.

In general, EA requires more research before it can be logically integrated into the supply chain/organizational level. More practical applications of EA will eventually help in emphasizing the value of such a holistic tool for not only ecological assessment but also managerial and operational evaluation.

The fourth chapter lays the theoretical groundwork for this dissertation thesis. It also examines numerous organizational theories that inform the study’s theoretical development.

CHAPTER 3 : THEORETICAL BACKGROUND AND FRAMEWORK

This chapter reviews a number of theoretical lenses to support the underlying research questions, hypotheses, and methodology selected. The theoretical focus will be on sustainable supply chain management (SSCM) practices and responses. The natural resource dependence theory (NRDT) is used to support and explain relationships between the ecological system and human-dominated systems investigated by this research. NRDT helps explain the need and scope of the proposed methodology and research relationship investigations at the supply chain level. In the next lines, a number of ecological theories and their definitions, constructs, and applications are described, emphasizing the major contrasts between these theories and the NRDT.

3.1 Theoretical Background

This research will consider broader aspects of supply chains, taking into account the external factors that affecting organizations' relationships and performance.

Organizations can be viewed as a network of social, economic, and professional relationships that interact dynamically with their surrounding environments. Building on this idea, the concept of resource dependence was introduced in 1970s to help explain related economic issues, such as mergers and board interrelations, in an attempt to provide an alternative theoretical grounding for economic theories of organizational relationships (Pfeffer and Salancik, 2003).

According to a number of literature review studies, resource dependence theory (RDT) is broadly used in the supply chain context to address collaboration with suppliers and customers, organizational interdependency, and uncertainty issues—and it has almost always been integrated with other theories to provide a holistic theoretical perspective on a specific area (Chen et al., 2017;

Delke, 2015; Ozturk, 2021). RDT focuses on the interrelated relationships between organizations to manage their degree of dependency on the external environment (Pfeffer and Salancik, 1978). RDT suggests that an organization's ability to competitively thrive is determined by its organizational capability to obtain critical resources whose sources lie outside the organization's boundaries. A source is considered critical if it is essential to the organization's survival in the market (Pfeffer and Salancik, 2003).

RDT assumes that organizations operate within an open system that allows for the continuous exchange of materials and information. Thus, organizations function in an uncertain environment (Nienhüser, 2008). The level of uncertainty depends on the distribution of critical resources.

Organizational interdependencies are determined by three factors (Pfeffer and Salancik, 1978): (1) criticality of the resource needed to survive in current environment; (2) degree of control and ownership of the critical resource; and (3) availability of alternatives.

At the strategic level of analysis, there are five different strategies to reduce interdependency and uncertainty: (1) mergers and acquisitions; (2) joint ventures; (3) boards of directors; (4) political action; and (5) executive succession (Pfeffer and Salancik, 1978). Organizations that are highly dependent on external resources adopt these strategies in an attempt to reduce interdependencies and thus absorb competition (Hillman et al., 2009; Pfeffer, 1972a). These strategies are useful in acquiring power and securing a consistent resource supply to reduce uncertainty, which is especially important as interorganizational relationships grow increasingly complex (Pfeffer, 1987).

RDT provides insight into the relationship between board size and external resources. Boards of directors can facilitate the procurement of critical external resources that are essential to sustain anticipated organizational performance (Kroll et al., 2007; Pfeffer, 1972b). The linkages between regulatory actions and interdependencies can help organizations control external resources (Hillman et al., 2009). Studies show that intra-organizational distribution of control and power is affected by degree of dependency on the external environment (Hillman et al., 2009; Weiner, 1984).

Although RDT is widely used to address environmental uncertainty issues (López-Gamero, Molina-Azorín, et al., 2011) opportunities for new insights still exist. RDT has been used to investigate relationships across organizations from a greening/sustainability perspective (Chand and Tarei, 2021; Sarkis et al., 2011; Schnittfeld and Busch, 2016); however, the direct relationship between organizations and their natural environment has been neglected (Bergmann et al., 2016).

Due to the vital significance of natural resources and their effect on organizational performance, Tashman (2011) introduced a new dimension to RDT by adding an ecological perspective, thereby creating NRDT. NRDT considers the dependency between organizations and their natural environment as that of resources being exchanged from one party with more power and control to a dependent party. The difference between RDT and NRDT is that the latter incorporates the natural environment as another actor in organizational resource exchange. Initially, NRDT posited that organizations are directly and indirectly dependent on natural resources, such the sun, water, energy, minerals, vegetation, animals, and air. Tashman (2011, p. 62) describes natural resource dependence as "a function of organizational ecosystem dependence, ecological impacts on organizations, and organizational impacts on ecosystem rather than organizational interdependence."

In NRDT, organizational behavior and performance are affected by social systems as well as ecosystems. Additionally, the developed construct of NRDT addresses mutual effects between organizations and their natural environment in a way that some ecological theories overlook. For NRDT, organizations and the natural environment interact directly with one another, and there is dependence in this relationship.

The ecological impact on organizations is reflected by forces of nature that can cause uncertainty and ultimately affects organizations' ability to obtain critical natural resources (Tashman, 2011). According to NRDT, organizations that are highly dependent on natural resources are likewise highly susceptible to natural forces that are nearly impossible to manage (de Abreu et al., 2017; Winn et al., 2011). Thus, ecological impacts on organizations are influenced by their degree of dependency on natural resources.

In the reciprocal relationship between organizations and the natural environment, organizational activities place numerous pressures on the ecosystem; overconsumption of natural resources and organizational waste are some of the most salient examples of the impacts organizations have on the environment. However, as many organizations become more environmentally conscious, some are developing sustainable practices initiatives to conserve natural resources.

NRDT is not extensively used in the SSCM literature. The literature review presented in Table 2-2 shows a lack of integration between NRDT and EA within the SSCM context, and recent research in SSCM using well-known, empirically tested theory remains underdeveloped. Only a few studies within the SSCM context have used NRDT as a theoretical lens to address sustainability issues. For instance, (Bergmann et al., 2016) used NRDT to explain the effect of extreme weather conditions on organizational performance—specifically, financial performance.

NRDT integrated with EA and SSCM contributes to the theory's practical and conceptual advancement in several respects. First, the developed models consist of ecological entities that are highly connected and interrelated, and which can be adequately explained by the broad concepts of NRDT.

Second, there are few, if any, studies within the SSCM literature that have integrated the methodologies presented in this research with the proposed theoretical lens, as shown in Table 2-2. This is particularly important because integrating emergy with NRDT explains the mutual relationship between organizations and their natural environment from a different perspective; that is, the real ecological cost of generating a product or service is evaluated in relation to dependencies, ecological impact, and organizational impact. Additionally, integrating NRDT with the emergy system dynamic (SD) model extends the analyses to investigate the role of policies in the natural resource dependence of various by-products within circular activities for supply chains. For instance, the emergy SD model may be able to investigate the role of policies on natural resource dependence over time, which would provide an effective tool for policymakers to assess the impact of certain policies as well as for organizations to manage their supply chain-related decisions.

Third, this research expands the theoretical perspective of the NRDT to include the utilization of EA in a sustainable supply chain and circular context. Moreover, the theory is further developed by introducing new indices to evaluate its constructs using emergy-based indicators (e.g., emergy loading ratio, emergy sustainability index). Such augmentation of the NRDT can encourage its wider adoption and provide a more objective measure for research and practice.

Thus, this integration of NRDT, EA, and supply chains provides new insights into SSCM. The resource-based view (RBV) (Barney, 1991) and the natural resource-based view (NRBV) (Hart, 1995), are internally focused (i.e., within the organization). By contrast, NRDT captures broader aspects of supply chains because it is more externally oriented. EA, however, offers value by integrating both internal and external perspectives, as will be described later in Chapter 5. EA can be a valuable tool for integrating NRDT with RBV's or NRBV's theoretical and methodological perspectives. NRDT can be reflected in emergy by measuring the dependencies on non-renewable resources and imported resources (these issues will be revisited in later chapters).

In light of these potential advantages of such integration, the application of NRDT to SCM is an emergent area that must be developed and tailored to address SSCM issues and practices. Table 3-1 summarizes the theories discussed above and highlights theoretical constructs of RDT, NRDT, and NRBV.

Table 3-1: Theories and Constructs

Theory	Construct	Author
RESOURCE DEPENDENCE (RDT)	- Managing the interrelated relationships between firms that rely on each other for needed goods and materials. - Views at organizations as an open system that consistently exchanges materials and information with the surrounding environment. - RDT focuses on organizational and environmental relationships.	Pfeffer and Salancik (1978)
NATURAL RESOURCE DEPENDENCE (NRDT)	- Organizations are directly and indirectly dependent on the natural resources (sun, air, water) (are they dependent on one another's natural resources?) - Natural resources and organizations are the two essential elements of NRDT.	Tashman (2011)
NATURAL RESOURCE-BASED VIEW (NRBV)	- Building a competitive advantage based on the relationship between the organization and the natural environment. - Make use of environmental strategies to use resources for better environmental performance (i.e., pollution prevention, product stewardship, and sustainable development).	Hart (1995)

3.2 Theoretical Framework

Combining the constructs and elements of RDT and NRDT, this thesis proposes that interactions between organizations and their supply chains with the natural environment should be made explicit. The framework emphasizes how dependencies and uncertainties play a role in supply chain environmental performance. Figure 3-1 shows the integrated constructs framework for both the RDT and the NRDT and summarizes these interrelations.

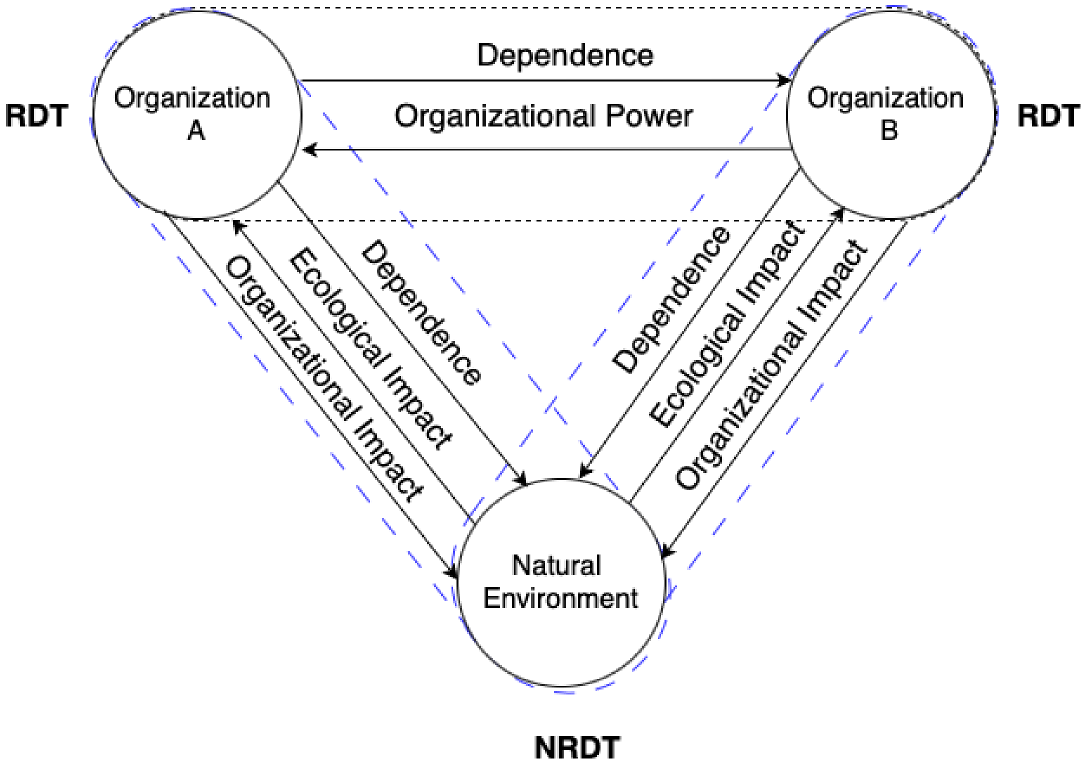


Figure 3-1: RDT and NRDT Integrated Construct

The uppermost portion of Figure 3-1 highlights the interorganizational relationships between two organizations, where organization A is dependent on organization B, which consequently has power over organization A (Pfeffer and Salancik, 1978). This power persists as long as organization B is in possession of a critical resource needed by organization A (Hillman et al., 2009).

The lower portion of Figure 3-1 considers the role of the natural environment and its relation to individual organizations. Organizations are dependent on the natural environment because they use resources naturally generated by the ecological system, such as water, sun, and soil. The natural environment also places some constraints on organizational performance, especially through events such as unpredicted natural forces. On the other hand, organizational activities impact the natural environment either positively (such as through regenerative green initiatives) or negatively (such as through resource depletion and waste generation).

In reference to various literature streams, a conceptual framework (Figure 3-2) is developed to expand current applications of EA and policymaking at the supply chain level (Pfeffer, 1987; Tashman, 2011). The proposed case study (which will be discussed in Chapter 4, Section 4.1) is intended as an ideal use case to demonstrate this framework. Specifically, the supply chain under study embodies a wide range of organizational and environmental (natural) relationships.

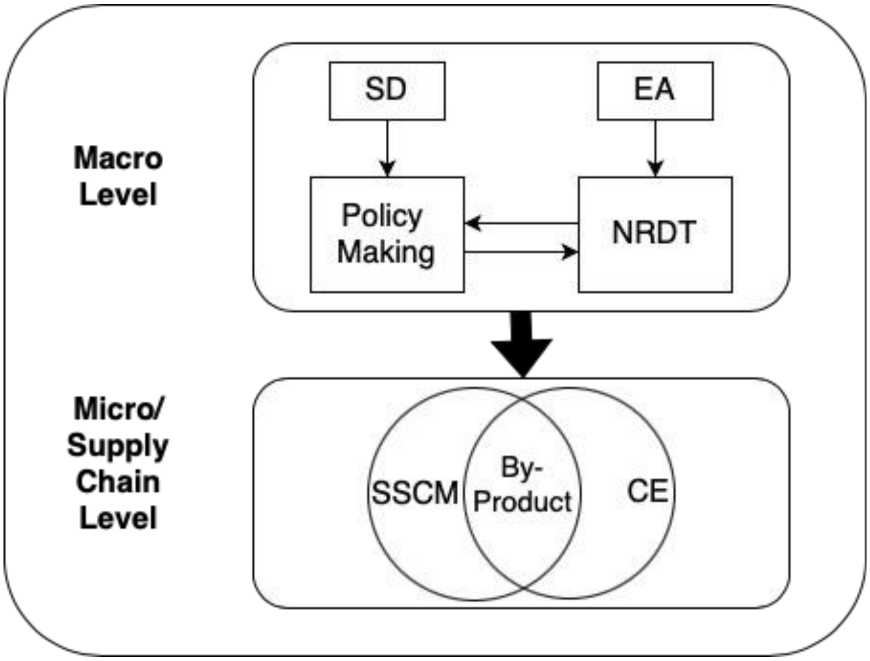


Figure 3-2: Conceptual Framework

Traditionally, the majority of the relevant literature uses EA and SD to address the macro level of analysis, usually affecting regions and general policy. The theoretical framework in this study aims to narrow down the applications of EA and policymaking from a very broad, non-operational perspective to the SSCM decision level. More specifically, a CE supply chain case study is used wherein decisions related to by-product sourcing—at an organizational level—are discussed and evaluated. Furthermore, emergy evaluations incorporate elements of NRDT, shifting it from the industry level (Tashman, 2011) to SSCM-level evaluation.

The RDT and NRDT can both be used as a theoretical foundation to understand the dynamic relationship between organizations and the environment in which they operate under government policies and regulatory pressure (Aragón-Correa and Sharma, 2003). Combining the underlying principles of the RDT and NRDT with state-level policy interventions to address uncertainty and dependencies may result in diverse outcomes at the organizational level (Choi et al., 2021; Hillman et al., 1999). For instance, regulatory actions taken by government authorities may raise the degree of uncertainty by restricting access to particular resources, impacting organizational and supply chain decisions concerning critical resource acquisition (Darby et al., 2020). From the perspective of RDT, Darby et al. (2020) investigated the impact of uncertainty caused by government policy on organizational ability to access critical resources. Moreover, Hillman et al. (2009) highlighted the linkages between regulatory actions and interdependencies as an attempt by organizations to manage their control over external resources. In general, various studies indicate growing organizational dependency as a result of government policies (Aharoni et al., 1981; Birnbaum, 1985; Meznar and Nigh, 1995; Pfeffer and Salancik, 1978).

From the viewpoint of NRDT, government policies can ultimately be imposed to mitigate the environmental impact caused by natural forces such as climate change, which affects the availability of natural critical resources and thus affects the impact of natural resources on organizations (Tashman, 2011). Resource conservation policies in Saudi Arabia have similar implications in terms of creating organizational dependence and uncertainty. In particular, The Saudi government has sought to curb water use by suspending wheat and fodder cultivation under Royal Decree No. M/66 (Ministry of Environment Water and Agriculture, 2018a; Royal Decree No. M/66, 2015).

3.3 Study Objectives

This section provides an overview of the motivation for this dissertation thesis. First, the main gaps in the literature are identified, after which the research objectives and research questions are enumerated.

Within the several literature streams concerning environmental assessment tools mentioned in Chapter 2, a number of gaps exist. First, only a few studies have integrated SD with EA, none of which targeted the supply chain level of analysis with practical applications (He et al., 2020). Second, the joint literature of EA and SSCM lacks an organizational theory-driven approach within a sustainable supply chain and CE context (Alkhuzaim et al., 2021). Third, although SCM practices are strongly influenced by government policy and regulatory actions, the current literature overlooks the significance of such issues within supply chains, especially in the context of sustainability and CE (Fugate et al., 2019; Sembiring et al., 2020; Tokar and Swink, 2019).

To fill the gaps, expand NRDT application and theory, and address specific CE concerns, this research incorporates a real case study adopting an integrative emergy system dynamic approach with a natural resource dependence perspective. The case study focuses on Aramco's circular supply chain of date seed by-products for the manufacture of lost circulation materials for drilling operations. Walnut shells were previously used for this purpose until the Saudi Ministry of Agriculture began facilitating the supply of date waste to Aramco as an environmental initiative to encourage circular activities. It is hoped that the comparison between the use of walnut shells versus date seeds from an emergy perspective will shed light on the feasibility of Saudi government policies seeking to support sustainable development in the Kingdom. A variation of results in terms of emergy requirements may provide insights as to whether the decision was more broadly warranted from a sustainability perspective as measured by emergy accounting.

Government polices (pressures) have played a role in Aramco's decisions to shift toward a circular supply chain structure (Aramco, 2018). Using EA and SD, the outcomes of such policies can be tested. Furthermore, the creation of an experimental SD model can help decision-makers assess potential and implemented policies. The theoretical arm of this investigation seeks to determine whether—and if so, how—natural resource dependence (based on NRDT) (Tashman, 2011) is influenced by government policies. Insights into how government policies' implications are measured and assessed from an NRDT perspective represent a significant practical and theoretical contribution of this research, which provides supply chain scholars and practitioners with theoretical and empirically driven supply chain mitigation strategies dealing with government policies.

In accordance with Resolution No. 180 of the Council of Ministers, Aramco stock started trading on the Saudi Stock Exchange on December 11, 2019, providing an opportunity for the company to attract international investors. Because some of these potential investors espouse a strong commitment to environmental responsibility, Aramco, as a large local oil company, is all the more motivated to alter the public's perception of the petroleum industry. In fact, in 2018, the Saudi Exchange announced a partnership with the United Nations' Sustainable Stock Exchanges (SSE) initiative, which emphasizes the importance of adopting sustainable practices for all listed companies. Working to achieve the UN's Sustainable Development Goals (SDG), the Saudi Stock Exchange offers a disclosure agreement of environmental, social, and corporate governance (ESG) practices for listed companies (SaudiExchange, 2018). In the case of Aramco, the use of date seed by-products to improve its environmental footprint reflects the growing pressure on all companies to adopt more sustainable and environmentally conscious practices, which in turn highlights the growing importance of environmental performance assessment tools (such as EA) for circular supply chains. This dissertation thesis aims to shed light on the outcomes of such policies over time from emergy and SD perspectives, thereby providing various insights to the decision-makers in this supply chain.

3.4 Research Questions and Hypotheses

In light of the previously described aspects of the proposed case, research questions can be addressed accordingly from SCM, SSCM, and policymaking contexts. Furthermore, a series of specific and exemplary case studies are developed. Thus, this dissertation research aims to answer the following questions:

- Research question 1 (R1): Can emergy analysis aid theoretical and practical environmental assessment at the supply chain level within a CE context?
    - Research question 1a (R1.a): What by-product alternative is better from an emergy accounting perspective?

This first question focuses on EA's capacity for integration into the supply chain level from the perspective of NRDT introduced by Tashman (2011). Furthermore, aspects of SSCM practices—CE in particular—will be tested as well. R1 will be answered as follows:

NRDT will be incorporated to narrow down the focus of EA from a broad environmental level to a CE supply chain level. Then, emergy-based indicators will be used to evaluate the theory's three main elements: (1) ecological impact on organizations, (2) dependency on natural resources, and (3) organizational impact on natural system and dependency on natural resources. For instance, the ecological impact on organizations is a function of organizational dependency on the ecosystem, and the percentage of non-renewable emergy of the total emergy can give insights about the degree of organizational dependency on the natural environment. A high percentage of non-renewable resources may indicate greater dependency. Emergy indicators, such as emergy load ratio (ELR), emergy yield ratio (EYR), and emergy sustainability ratio (ESR), can also be used to evaluate organizational impact on natural resources. One practical implication of these elements is that they help organizations make difficult business decisions related to supply chains.

Based on the case study of Aramco's supply chain for lost circulation materials, the first sub-question (R1.a) is answered. Date seeds and walnut shells, which represent the two alternative sources of raw materials for manufacturing lost circulation materials, are compared from an emergy standpoint. In particular, emergy indicators can assist in identifying the more sustainable alternative from a donor-side perspective as opposed to a user-side one. According to the employed case study, a series of hypotheses are developed.

Hypothesis 1: Because they are locally sourced, date seed supply as a by-product is more sustainable than walnut shell supply from an emergy perspective.

The first hypothesis is supported by the fact that Saudi Arabia is the second largest producer of dates, generating around 150,000 tons of date seeds each year (Amanullah et al., 2017; Hamden et al., 2022). With the availability of a local product that has the exact same properties as the imported walnut shells, date seeds are more economically and environmentally viable, as suggested by Saudi Aramco's lead engineer at the Exploration and Petroleum Engineering Research Center, Dr. Amanullah (Amanullah et al., 2017; Amanullah et al., 2016). This is also supported by the literature, where many studies have highlighted the negative environmental impact of global supply chains by means of increasing pollution and environmental pressure caused by unsustainable practices in general (Clift and Wright, 2000; Cruz, 2013; Mollenkopf et al., 2010) and transportation in specific, considering the extended travel distance (Levy, 1995).

Furthermore, the transportation of each by-product is different: walnut shells represent a global supply chain whereas date seeds represent a local one. Walnut shell by-products are assumed to be delivered by sea or air, whereas date seed by-products are delivered by road (trucks). Based on the results of a study by Corcelli et al. (2018), the transformity of sea transportation of woodchip is lower than that of road-transported woodchip; it is assumed that this finding can be generalized to walnut shells and date seed by-products. As such, we hypothesize that switching from a global to a local supply chain will yield some economic and environmental benefits by cutting the cost of importing walnuts and reducing the environmental harms associated with transportation activities and the disposal of date seeds as agricultural waste.

The second hypothesis focuses on the environmental pressure caused by supply chain operations on the natural environment, which is measured using the ELR.

- *Hypothesis 2: The date seed by-product supply chain exerts lower environmental pressure on the natural system than the walnut shell by-product supply chain.*

The third hypothesis focuses on the level of sustainability of the two evaluated supply chains and how they may impact the natural environment. This hypothesis is measured using the ESI.

- *Hypothesis 3: The impact of the date seed by-product supply chain on the natural environment is more sustainable than the walnut shell supply chain.*

The fourth hypothesis focuses on the level of efficiency in exploiting local resources. Testing this hypothesis may give an indication of the organization’s dependence on the natural environment, which, if increased, would result in a higher ecological impact on the organization. This hypothesis will be tested using EYR.

- *Hypothesis 4: Because of better exploitation of local resources, the ecological impact on the walnut shell by-product supply chain is greater than that of the date seed by-product supply chain.*

The fifth hypothesis demonstrates the efficiency with which local resources are used. It indicates that the efficient utilization of local resources reduces dependence, thereby mitigating some of the ecological impact on the organization. This hypothesis will be tested using the emergy investment ratio (EIR).

- *Hypothesis 5: Because of a high utilization level of local natural resources, the date seed by-product supply chain is less dependent on the natural environment than the walnut shell by-product supply chain.*

Hypotheses 2–5 are based on the fact that because date seed by-products are local agricultural waste, the impact of their domestic supply chain on the natural environment is lower than that of the walnut shell by-products' global supply chain. Considering the spatial dimension, a global supply chain may impose a higher level of environmental pressure. Indeed, a number of studies have indicated that global supply chain transportation activities are the leading source of carbon emissions, with sea transportation accounting for 75% of that total (Tantiwatthanaphanich et al., 2022), in addition to the high consumption of energy and natural resources (Sovacool et al., 2021; Tubiello et al., 2021).

- Research question 2 (R2): How does government policy play a role in natural resource dependency (organizational decisions) in a supply chain by-product (CE) setting?

This question aims to test the impact of two policies using SD modeling from the perspective of EA at the supply chain level, which represents a methodological contribution. The two policies are government subsidy (P1) and environmental concerns (P2). To answer R2, four steps must be completed. First, the emergy diagram will be replicated in SD modeling language using Stella software to create an emergy SD model. Next, elements of the NRDT will be evaluated using emergy-based indicators. Then, several scenarios will be tested with a combination of the two proposed policies (P1 and P2), including the baseline scenario. Finally, simulation results will be compared with the baseline scenario after policy implementation.

The emergy SD model takes into account only the upstream segment of the date seed by-product circular supply chain: date cultivation. The SD model is limited to the date cultivation activities of the investigated supply chain because, from an emergy perspective, date cultivation processes are the greatest contributor to the date seed by-product supply chain's total emergy because this is the only phase of the supply chain that includes the use of natural resources (renewable and non-renewable). In fact, the scope of the tested policies is closely tied to regulating agricultural practices that focus on the use of natural resources, particularly influencing the upstream supply chain. Furthermore, the ripple effect of governmental initiatives may extend to other supply chain tiers, thus affecting organizational decisions on sourcing alternatives from a broader perspective (Lee et al., 2014). After the intended policies are implemented, the impact of policy intervention extends to the downstream parties of the supply chain being studied. In particular, emergy-based indicators of the two by-products—date seeds and walnut shells—will be re-evaluated in comparison to the baseline scenario analyzed in Chapter 5, Section 5.1 to assess the role of broader policy in natural resource dependency in a supply chain by-product setting.

For R2, two hypotheses are developed.

- *Hypothesis 6: The percentage of non-renewable resources used in the date seed by-product supply chain is lower due to the impact of a government subsidy policy.*

This hypothesis indicates that when government subsidy policy is implemented, the consumption of non-renewable resources decreases. In other words, the policy encourages the implementation of modern irrigation systems that consume less groundwater (a non-renewable resource), which illustrates both lower dependence and a lower ecological impact. The degree of ecological impact is informed by the NRDT construct, which suggests that when an organization is less dependent on critical natural resources, the unpredictable impact of the ecological system on the organization's operation is reduced.

- *Hypothesis 7: The environmental pressure is reduced as a result of Saudi Arabia's regulatory environmental actions.*

This hypothesis reflects the effectiveness of the second policy (i.e., environmental concerns) on the overall environmental pressure of the date seed by-product supply chain. The policy aims to increase the production of dates while reducing the environmental pressure imposed by this expansion. From the NRDT perspective, this hypothesis indicates that the second policy helps reduce the organizational impact on the natural environment measured by the ELR.

The main contributions and objectives of this research are: (1) advancing the practical use of performance measures in general and environmental performance measures in particular for SSCM practices; (2) expanding the practical applications of EA at the supply chain level with a greater focus on supply chain-related decisions; (3) expanding and linking organizational theory to EA by testing elements of the NRDT using the proposed methodology; and (4) using SD as a policymaking tool to support supply chain-related decision-making.

Answers to the research questions will stem from applying the employed methodology to the specific case study of date seed by-products in Saudi Aramco, an important process with noteworthy environmental implications. The case study of Aramco's circular supply chain and the data collection process are presented in Chapter 4.

CHAPTER 4 : CASE STUDY AND DATA COLLECTION

Given the practical, theoretical, and research backgrounds described in the three preceding chapters, this fourth chapter describes the environment of the case study that will be analyzed in detail to investigate and advance the research questions and hypotheses. This approach constitutes an inductive approach to investigate more detailed hypotheses related to the research questions posed in the previous section.

An integrative case study methodology for date seed by-products by Saudi Aramco, representing a circular economy (CE) supply chain setting, can guide us toward answers to the research questions enumerated in the preceding chapter. This chapter describes the elements and details of the circular supply chain under study, which is an important case with environmental implications. Within the methodological description, the chapter concludes with a discussion of the data collection process for R1, which concerns emergy analysis (EA) investigation and its relationship to the natural resource dependence theory (NRDT), as well as policy relationships related to R2.

The preceding chapters have shown that within the integrated supply chain management (SCM) and EA literature, a vast majority of published studies are not theoretically driven—especially when emergy is used as a methodology rather than as a theoretical base. This theoretical lacuna in the literature may pose a barrier to further understanding of EA within the SCM context. Moreover, the integration of system dynamics (SD) and EA needs further investigation at the SC level; of the few sustainability studies that have employed SD and EA approaches, all did so to evaluate sustainability at the level of regions and cities.

Our research addresses this gap and advances the field of SCM and CE investigation by combining SD modeling with EA in the supply chain context as an integrative environmental performance measure from an NRDT perspective. Implementing the proposed methodology as a supply chain performance measure may encourage supply chains' stakeholders to be more transparent about disclosing information regarding product engineering and design systems, thereby improving the overall performance of supply chains (Alkhuzaim et al., 2021). Of course, proprietary information may be perceived as a competitive advantage, thereby limiting the efficacy of this performance measure (Tian and Sarkis, 2020).

The SD model is limited to the date cultivation activities of the investigated supply chain because, from an emergy perspective, date cultivation processes are the greatest contributor to the date seed by-product supply chain's total emergy because this is the only phase of the supply chain that includes the use of natural resources (renewable and non-renewable). In fact, the scope of the tested policies is closely tied to regulating agricultural practices that focus on the use of natural resources, particularly influencing the upstream supply chain. Furthermore, the ripple effect of governmental initiatives may extend to other supply chain tiers, thus affecting organizational decisions on sourcing alternatives from a broader perspective (Lee et al., 2014).

The emergy SD model is used to test two government policies and their implications on the emergy performance of date cultivation as well as the ramifications of these policies for supply chain decisions. The next section describes the case study, the policies used in the case study investigation, and the data collection process.

4.1 Case Study

The case study focuses on Aramco's circular supply chain of date seed by-products for the manufacturing of lost circulation materials. Aramco is a Saudi Arabian national petroleum and natural gas company. Based in Dhahran, Saudi Arabia, Aramco is one of the largest oil companies in the world.

As an environmental initiative to encourage circular activities, the Saudi Ministry of Agriculture has been facilitating the supply of date waste to Aramco, which eventually led Aramco to use date seed by-products instead of walnut shells as lost circulation materials in their drilling operations. According to Amanullah et al. (2016), Aramco developed the following six-step industrial process to transform date seed by-products into lost circulation materials: (1) washing the waste by-product of date seeds to remove any residues, (2) drying, (3) roasting date seeds using thermal treatment to remove any excess moisture, (4) grinding, (5) sieving ground seeds to separate particles of desired size, and (6) storing date seed particles awaiting transfer to drilling locations. These processes were developed by Saudi Aramco and constitute legally protected intellectual property. Date seed waste is processed by the National Factory located at MGWC+R8M, Al Oyun 36256, which is licensed by Saudi Aramco to use the six processes.

The drilling industry is characterized by intensive use of energy and other natural resources, as well as high import expenses associated with the required materials and additives. According to Alawad and Fattah (2019), in the oil exploration industry, drilling processes account for 25% of the total cost. In addition, drilling processes require the use of specific fluids, which themselves account for 15–18% of the total drilling operation cost.

Wells are drilled to extract natural resources such as water, oil, and natural gas from the ground. During drilling, drilling fluids are pumped into the ground to reduce non-productive time (Redden, 2009). Drilling fluids are used mainly to stabilize the wellbore (i.e., a hole drilled in the surface of the earth to extract natural resources), seal permeable formations, and extract cuttings from the well (Cook et al., 2011). Whenever one or more of the previously mentioned issues occur the drilling operations are suspended to re-stabilize the well to prevent blowout of natural resources. In this case, non-productive time is increased, which results in significant financial losses (Amanullah et al., 2017). Thus, proactive measures must be applied by using special drilling fluids. Table 4-1 provides more explanation of the usage of drilling fluids.

Table 4-1: Drilling Fluids Usage

Function	Purpose
Stabilize the wellbore	Maintain proper conditions during drilling operations to prevent failure in the rock around the well (Zeynali, 2012).
Seal the permeable formation	Minimize leakage of drilling fluids by plugging permeable formations underground (Cook et al., 2011).
Extract the cuttings	Move cuttings caused by drilling operations to the surface (Majid et al., 2019).

These fluids are created with specific characteristics to help in drilling operations, and their loss is very common—yet also very expensive, due to their great cost. According to the Exploration and Petroleum Engineering Center - Advanced Research Center (EXPEC-ARC) in Saudi Aramco, drilling fluid loss is one of the greatest challenges faced by operators, due to the cost of these fluids. According to Amanullah et al. (2016), imports of drilling fluid additives exceeded $50 million in 2012. Drilling fluids are most often lost to fractures in rock formations; to mitigate costly fluid loss, drilling companies are using specific materials, known as "lost circulation materials," to seal and plug such fractures.

For a time, Aramco used walnut shells as lost circulation materials (Amanullah et al., 2017), which were imported from the US to drilling locations in Saudi Arabia. The use of imported walnut shells added costs—such as transportation costs—to total operation costs. Thus, local sourcing of an equivalent material could offer significant economic savings while also lessening the environmental impact incurred by transporting walnut shells thousands of miles across land

and sea. Date seeds—cheap, plentiful, and local—appeared to be an ideal replacement for imported walnut shells: Saudi Arabia is the world's second-largest producer of dates—and, therefore, of date seeds (or date waste) (Hamden et al., 2022). According to Amanullah et al. (2017), the number of registered date palm trees in Saudi Arabia reached 20 million in 2003, plus 3.7 million additional unregistered date palm trees, generating a huge amount of date waste every year. From an environmental perspective, date waste (i.e., date seeds) is normally treated in a non-environmentally friendly way by burning the waste, which in turn releases harmful gases and carbon emissions. Alternatively, date waste is often buried, which creates a polluted environment. In addition to reducing the immediate environmental contamination caused by traditional means of date waste disposal, using date seed by-products to produce lost circulation materials would also eliminate the environmental impact of transporting walnut shells from the US. In more ways than one, using this natural—and, most importantly, local—renewable resource can minimize the environmental pressure placed on the ecosystem.

From an economic viewpoint, using a local by-product will not only reduce transportation cost and decrease local pollution due to improper disposal, but will also support the local economy in many different ways. Based on a market study by Aramco's commercialization team, the market value of the drilling fluids industry will likely grow by as much as $15.66 billion by 2026. Thus, demand for drilling fluids will increase, creating a new venue for investment in the local market for date seeds as a lost circulation material.

The Saudi government is introducing new policies such as Saudi Vision 2030, which positions sustainable development as a central national goal. According to the Saudi National Portal, another initiative—the National Environmental Awareness and Sustainable Development Program—aims to deal with environmental protection issues. The program supports increasing public awareness, making environmental problems a priority, and promoting environmentally friendly practices. Because Aramco is a very large company, its role in implementing this vision is essential. Moreover, Aramco is under tremendous pressure from regulatory bodies to adopt more sustainable practices (Aramco, 2018). In response, Aramco took some corrective actions by implementing more sustainable practices in their drilling operations—one of which is this policy of substituting (i.e., date seed for walnut shell) a local agricultural waste material for use in lost circulation material manufacturing.

Government polices (pressures) influence Aramco's supply chain decisions to shift to a circular structure of their supply chain (Aramco, 2018). SD modeling of this policy and institutional influence will be presented later in the study. The assumed relationships of these pressures will also be detailed. First, however, we describe a specific policy, or set of policies, that will influence Aramco's supply chain decisions.

In accordance with Resolution No. 180 of the Council of Ministers, Aramco stock started trading on the Saudi Stock Exchange on December 11, 2019, providing an opportunity for the company to attract international investors. Because some of these potential investors espouse a strong commitment to environmental responsibility, Aramco, as a large local oil company, is all the more motivated to alter the public's perception of the petroleum industry. In fact, in 2018, the Saudi Exchange announced a partnership with the United Nations' Sustainable Stock Exchanges (SSE) initiative, which emphasizes the importance of adopting sustainable practices for all listed companies. Working to achieve the UN's Sustainable Development Goals (SDG), the Saudi Stock Exchange offers a disclosure agreement of environmental, social, and corporate governance (ESG) practices for listed companies (SaudiExchange, 2018). In the case of Aramco, the use of date seed by-products to improve its environmental footprint reflects the growing pressure on all companies to adopt more sustainable and environmentally conscious practices, which in turn highlights the growing importance of environmental performance assessment tools (such as EA) for circular supply chains. This dissertation thesis aims to shed light on the outcomes of such policies over time from emergy and SD perspectives, thereby providing various insights to the decision-makers in this supply chain.

4.2 Data Collection

Although data collection for this research used some primary sources, most were secondary sources published by official government agencies in Saudi Arabia regarding the palm and date production sector.

Agricultural statistical data was obtained from the most recent official government records of the Ministry of Environment Water and Agriculture (2018a). Furthermore, additional data was generated from the National Center for Palms and Dates, which is an official government research center established in August 2011 to support the development and advancement of the date palm tree sector and date-related services and operations (The National Center for Palms and Dates, 2016, 2018a, 2018b). It is located at 8HPW+G4W, King Faisal University, Al Hofuf 36362.

Reports published by the National Center for Palms and Dates include some detailed data concerning common agricultural practices such as machinery, fertilizers, and irrigation systems used in growing and harvesting date palm trees. Additionally, data related to annual date production, planted area and gasoline consumption, as well as some environmental indicators, was generated from the General Authority for Statistics to perform emergy calculations (The General Authority for Statistics, 2015, 2018, 2020). For information related to government agricultural regulations and subsidy, data was collected from the published records of the Agricultural Development Fund (Agricultural Development Fund, 2019).

Evaluations conducted in this dissertation extend to include the US walnut production sector. The main sources of such data were official published agricultural government records, historical data, and published studies. Agricultural statistics were obtained from the recent published records of the United States Department of Agriculture (USDA, 2020a, 2020b).

The Aramco case study used in this research aims to provide a practical situation to introduce how emergy evaluation methodology can be used to investigate supply chain concerns as well as a substitution argument for two alternative sustainable resources.

Although motivated by a real case study, this study is not without some data limitations, causing greater reliance on secondary data and necessitating a number of assumptions. Aramco could provide only limited information due to its sensitive market position; as a result, some of the data collection process was interrupted. Dr. Amanullah, Aramco's lead engineer at the Exploration and Petroleum Engineering Center - Advanced Research Center (EXPEC-ARC), provided initial data regarding the sources of date seed by-products, the processes used to transform the date seed by-products into lost circulation materials, the type of machinery used during these processes, and the local factory where the by-products are transformed. The main challenge is that much of the requested data was classified as confidential; thus, initial information gathered from Aramco was confined to a single interview, with other significant information coming from sources such as published articles by the Exploration and Petroleum Engineering Center - Advanced Research Center (EXPEC-ARC) team (Amanullah, 2007; Amanullah et al., 2017; Amanullah et al., 2016; Ramasamy and Amanullah, 2017).

The supply chain under study is relatively long and involves multiple tiers, which caused additional challenges associated with supplier cooperation. Considering the aforementioned limitations of data collection, data specific to the investigated supply chain was estimated primarily with the aid of a number of experts in the industry, such as Mr. Khalid Al-Husaini and Dr. Yousef Al-Fuhaid, respectively the manager and researcher at the National Center for Palms and Dates in Al-Hasa; the founder of Al-Gosaibi Company, Mr. Saud Al-Gosaibi; Mr. Saeed Al-Rafaya from the Al-Rafaya Company; and published studies such as those by (Abdulrasoul et al., 2019; Al-Khayri et al., 2015; Alawad and Fattah, 2019; Aleid et al., 2015; Elfeky and Elfaki, 2019; Erskine et al., 2004; Kassem, 2007; Rahman et al., 2007; SABIC, 2021).

Expert opinions were solicited via verbal communications to gain some general practical data about the date processing industry and the secondary market of date seed by-products. For instance, to get the best estimate of the availability of date seeds in the market, a large-scale date paste factory was used as a generic example to estimate the distance from the date paste factory to the date seed by-products factory. Al-Ahsa Food Industries Company is used as a source for data for two reasons. First, the company is located in Saudi Arabia's Eastern Province, where Aramco and the date seed processing factory are located. Second, verbal communications with experts in the industry confirm that the factory performs a large-scale production, which gives an indication of the amount of waste (date seeds) generated that can be sold in a secondary market. The factory is located at CJ73+53 Al Mubarraz, approximately 42.3 km from the date seed by-product processing factory (the National Factory).

Data on walnut shell processing was drawn from a variety of references in published studies (Amanullah et al., 2017; Azubike et al., 2019). This study assumes that Aramco adopts the same processes to transform date seed by-products into lost circulation materials as those used for walnut shell by-products. Thus, taking into account the main differences between the two by-products, data estimated for evaluating the six processes performed on date seeds was also utilized to evaluate walnut shells.

The next chapter uses the data collected from multiple sources to perform extended emergy evaluations of the date seed and walnut shell by-product supply chains, including cultivation (Sections 5.1 and 5.2), transportation (Section 5.3), and processing into lost circulation materials (Sections 5.4 and 5.5).

CHAPTER 5 : EMERGY EVALUATION

In this chapter, emergy analysis (EA) is employed as an environmental performance measure to comparatively evaluate the performance of two supply chains. It is used to investigate Aramco’s supply chain of date seed by-products, including the upstream activities of producing dates and downstream activities of transforming date seed by-products into lost circulation materials used in Saudi Aramco drilling operations. EA is also used to evaluate the walnut shell by-product supply chain.

The emergy evaluations begin by determining the primary inputs and components for the two investigated systems, including material, energy, and information flows. The energy flows comprise renewable, non-renewable, and purchased inputs. These inputs are illustrated graphically using emergy diagram. Next, all of the primary inputs are converted into energy flows, and from there to solar equivalent values using conversion factors (i.e., transformities). The last step is the calculation of emergy-based indicators, aggregating all the emergy values of the different supply chain activities to assess the performance of the investigated systems informed by the natural resources dependence theory (NRDT). Figure 5-1 illustrates the main steps for conducting emergy evaluations of the date seed and walnut shell by-product supply chains.

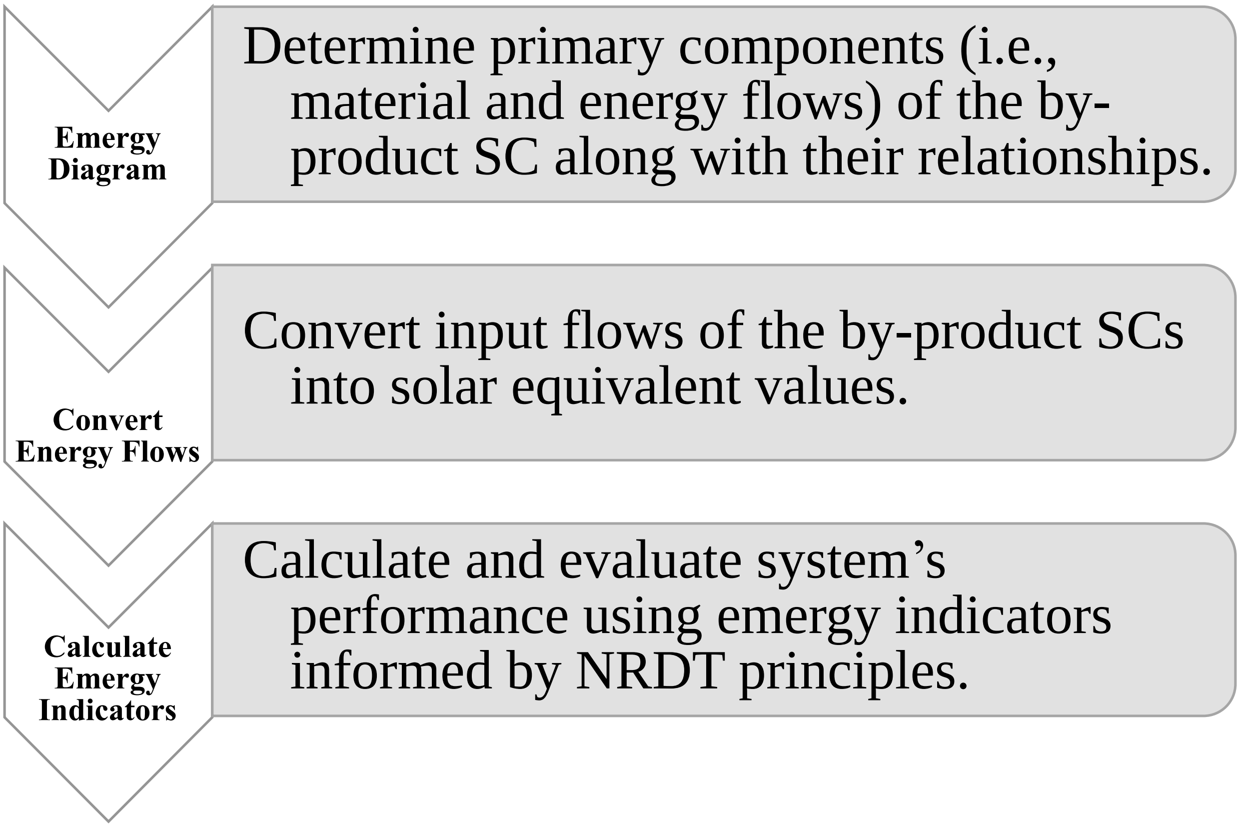


Figure 5-1: Emergy Analysis Framework

The chapter is structured as follows: Section 5.1 covers all inputs to the cultivation activities; Section 5.2 includes all inputs to walnut cultivation; Section 5.3 discusses the transportation modes used to deliver each by-product; Section 5.4 presents an emergy evaluation of Aramco's six transformative processes of date seed by-products; and finally, Section 5.5 provides an emergy evaluation of Aramco's six transformative processes of the walnut shell by-products.

Aramco's six transformative processes are performed on the date seed by-products, and this research assumes that the walnut shell by-products also go through the same processes to produce lost circulation materials. These processes are: (1) washing the waste by-product of date seeds to remove any residues, (2) drying, (3) roasting date seeds using thermal treatment to remove any excess moisture, (4) grinding, (5) sieving ground seeds to separate particles of desired size, and (6) storing date seed particles awaiting transfer to drilling locations.

According to Aramco's lead engineer at the Exploration and Petroleum Engineering Center - Advanced Research Center (EXPEC-ARC), Dr. Amanullah, these processes were developed by Saudi Aramco and constitute legally protected by intellectual property. Date seed waste is processed by a local company licensed by Saudi Aramco to use the six aforementioned processes.

Figure 5-2 shows all modeled processes using EA notations with respect to the natural renewable and non-renewable resources as well as imported materials. Emergy notations are described in Chapter 2, Section 2.5, Figure 2-1.

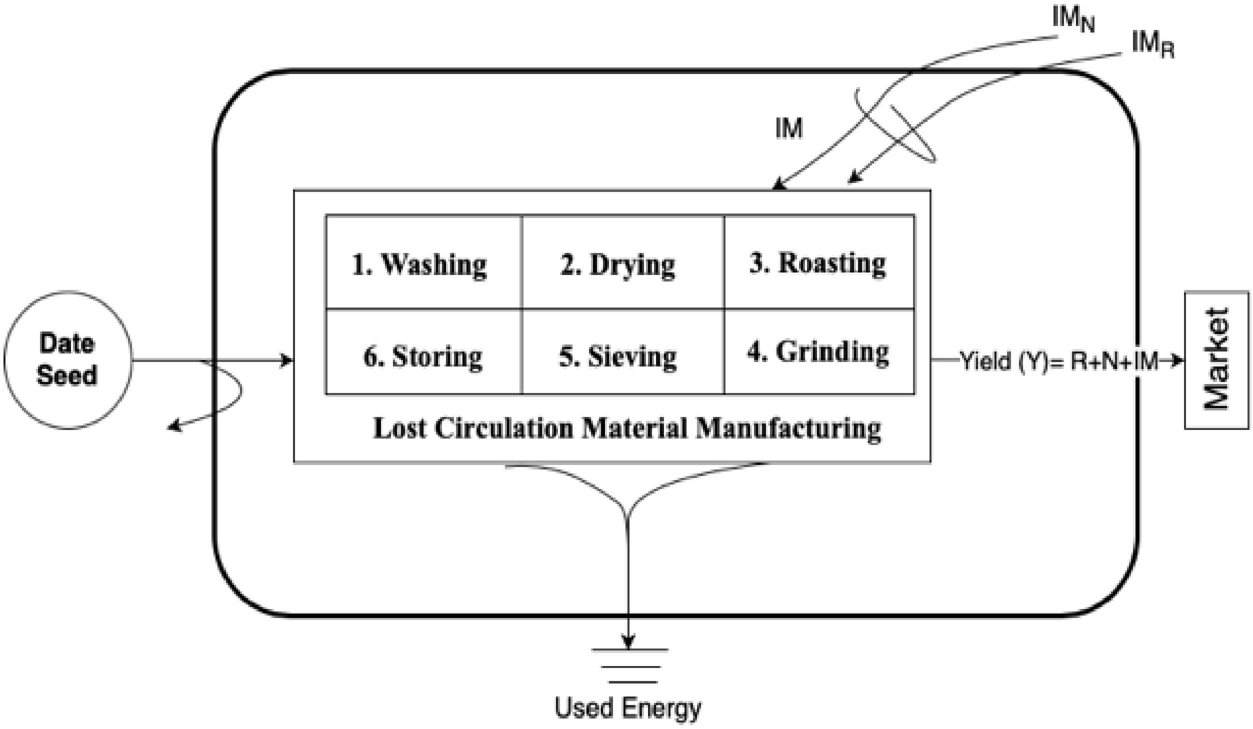


Figure 5-2: Emergy Diagram of the Lost Circulation Materials Manufacturing Processes

5.1 Emergy Evaluation of Dates Cultivation

Table 5-1 presents all the emergy inputs, including the emergy of renewable (R), non-renewable (N), and purchased (IM) resources as well as the labor and services (L&S) required to produce dates in Saudi Arabia. The following emergy calculations convert all the resources into energy then energy to emergy values.

The first column, “item,” represents the resources included in the evaluation. The second column, “raw amount,” is the available energy within each resource. The third column shows the unit used for each resource. The fourth column is the unit emergy value (UEV) for each resource, which represents all the previous environmental activities that have taken place to produce each resource. UEVs are used from previous studies, which are referenced in the fifth column. Finally, the sixth column presents the emergy value of each resource flowing into the system after conversion.

Table 5-1: Emergy Evaluation of Dates Cultivation

Item	Raw Amount	Unit	UEV (sej/unit)	Reference of UEV	Emergy flows (sej/yr)
Local renewable resources (R)					
Primary renewable flows					
1. Solar radiation	9.52E+18	J	1	(Odum, 1996)	9.52E+18
2. Geothermal heat	2.30E+14	J	4.90E+03	(Brown and Ulgiati, 2016)	1.13E+18
Sum of primary flows					1.07E+19
Secondary renewable flows					
3. Rain (chemical potential)	1.34E+14	J	7.00E+03	(Brown and Ulgiati, 2016)	9.35E+17
4. Wind	1.39E+16	J	8.00E+02	(Brown and Ulgiati, 2016)	1.11E+19
Max of secondary flows					1.11E+19
Subtotal					2.18E+19
Local non-renewable resources (N)					
5. Soil loss (organic matter)	5.84E+14	J	7.40E+04	(Odum, 1996)	4.32E+19
6. Groundwater	4.49E+15	J	4.10E+04	(Odum et al., 1995)	1.84E+20

Subtotal					2.27E+20
Purchased (imported) resources (IM)					
7. Diesel	2.79E+15	J	6.60E+04	(Odum, 1996)	1.84E+20
8. Gasoline	2.51E+13	J	6.60E+04	(Odum, 1996)	1.66E+18
9. Machinery	1.54E+08	g	6.70E+09	(Arding and Brown, 1991)	1.03E+18
10. Fertilizers					
Nitrogen (N)	3.07E+07	J	1.69E+06	(Odum, 1996)	6.08E+13
Potash (K_2O)	9.00E+06	J	2.63E+06	(Odum, 1996)	2.37E+13
Phosphate (P_2O_5)	6.40E+02	J	1.78E+10	(Odum, 1996)	1.14E+13
Subtotal					1.87E+20
Labor and Services (L&S)					
11. Labor (L)	1.10E+04	$/yr	--	(NEAD, 2008)	6.74E+16
12. Services (S)	4.66E+08	$/yr	--	(NEAD, 2008)	2.84E+21
Subtotal					2.84E+21
Total Emergy (with L&S)					3.28E+21
Total Emergy (without L&S)					4.36E+20
Dates' mass	1.54E+12	g	--	(The General Authority for Statistics, 2018)	--
percentage of generated date seeds byproduct	15%	--	--	(Kamel et al., 1981)	--
Energy content (dates)*	2.02E+16	J	--	(Al-Farsi and Lee, 2008)	--
Specific dates emergy (with L&S)[1]	--	sej/g	2.13E+09	This study	--
Specific dates emergy (without L&S)[2]	--	sej/g	2.83E+08	This study	--
UEV of date seeds (byproduct) [3]	--	sej/g	4.25E+07	This study	--
UEV (with L&S)[4]	--	sej/J	1.62E+05	This study	--
UEV (without L&S)[5]	--	sej/J	2.16E+04	This study	--

Units are defined in the appendix, Table 10-1.

[*] Energy content per gram of dates is 1.31E+04 J (Al-Farsi and Lee, 2008). For the mass of dates produced, the energy content is 1.54E+12*1.31E+04=2.02E+16.

[1] Specific dates emergy (with L&S) = Total emergy (with L&S) 3.28E+21/ Dates mass 1.5412.

[2] Specific dates emergy (without L&S) = Total emergy (without L&S) 4.36E+20/ Dates mass 1.5412.

[3] UEV of date seeds (byproduct)= Specific dates emergy (without L&S) 2.83E+08* 15% percent of generated reusable date seeds.

[4] UEV of date seeds (with L&S)= Total emergy (with L&S) 3.28E+21/ Energy content 2.0216.

[5] UEV with labor and services= Total emergy (without L&S) 4.36E+20/ Energy content 2.02E+16.

All energy sources and material resources flowing into and stored within the investigated system are graphed using the emergy systems language (Chapter 2, Section 2.4), and the quantities were converted into energy units (joules), mass units (grams), or monetary units ($ US dollar). All emergy equations are presented below.

1. Solar energy (J) = (Cultivated area)*(Insolation)*(1-Albedo).

- Cultivated area= 1.18E+09 m^2 (The General Authority for Statistics, 2020).
- Insolation= average hours of sunshine = 8.89 hours per day (Pazheri, 2014), (8.89*365) 3.24E+3 h/yr * 3.60E+6(J/m^2/yr)= 1.17 E+10 J/m^2/yr.
- Albedo: The average albedo over Saudi Arabia is between 0.25 -0.36 (Maghrabi and Al-Mostafa, 2009) an approximate middle value is used in this research 0.31.

Solar energy (J) = (1.18E+09 m^2) * (1.17 E+10 J/m^2/yr.) *(1-0.31) = 9.52 E+18 J/yr.

2. Geothermal Heat Energy (J) = (Cultivated area) *(Heat flow per area)*(Carnot efficiency).

- Area= 1.18E+09 m^2 (The General Authority for Statistics, 2020).
- Heat flow per area = 2.05E+06 J/m^2/yr (Yu et al., 2020).
- Carnot efficiency= 9.5% (Brown and Ulgiati, 2016).

Geothermal Heat Energy (J) =(1.18E+09 m^2) *(2.05E+06 J/m^2/yr)* (9.5%)= 2.30E+14 J/yr.

To avoid possible double-accounting for the free renewable inputs (sunlight, rain, wind, and geothermal heat), only the largest contribution, the rain in the present case, is taken into account as suggested by Odum (Odum, 1996).

3. Rain, chemical potential energy (J) = (cultivated area) *(rainfall) *(transpiration rate) *(water density) *(gibbs energy of rain).

- Area= 1.18E+09 m^2 (The General Authority for Statistics, 2020).
- Rainfall per year= average rainfall from two regions in Saudi (Qassim and Al Jouf) is 263.92 m3/ha/year or (0.03 m^3/m^2/year) ≅0.03 m/yr (Abdulrasoul et al., 2019).

- Transpiration rate= 80% estimated from (Ismail et al., 2014).
- Water density= 1000 kg/m^3.
- Gibbs energy of rain = 4.72 J/g, (Brown and Ulgiati, 2018).

Rain, chemical potential energy (J) = (1.18E+09 m^2) *(0.03 m/yr)*(0.80)*(1.00E+06 g/m^3)*(4.72J/g) = 1.34E+14 J/yr.

4. Wind energy (J) = (cultivated area)* (air density) *(drag coefficient) *(geostrophic wind velocity) ^3.

- Cultivated area= 1.18E+09 m^2 (The General Authority for Statistics, 2020).
- Air density= 1.23 kg/m^3.
- Drag coefficient = 1.64E-03 (Garratt, 1994).
- Geostrophic wind velocity = Annual average wind speed/0.6 = 3.4/0.6 m/s = 5.7 m/s (The General Authority for Statistics, 2015).

Wind energy (J)= (1,178,810,000 m^2) (1.23 kg/m^3)*(1.64E-03)*(5.7 m/s)^3*(3.154E+07 s/yr)= 1.39E+16 J/yr.

5. Soil loss (organic matter):

Net loss of topsoil = (cultivated area) *(erosion rate). The energy of soil used, or lost = (net loss topsoil) *(% organic matter)*(5.4 kcal/g)*(4186 J/kcal).

- The mean soil erosion calculated using Universal Soil Loss Equation (USLE) model is estimated to be 16.10 ton/ha/yr or 1460.57 g/m2/ yr (Mallick et al., 2016) .
- % organic matter= 1.5% (Mallick et al., 2020).

Net loss of topsoil= (1.18E+09 m^2) * (1460.57 g/m^2/yr)*(1.5%)*(5.4 kcal/g)*(4186 J/kcal)= 5.84E+14 J/yr.

6. Groundwater = (water volume m^3/yr) * (density g/m^3) * (gibbs free energy)

The consumed water volume varies depending on the irrigation system used to irrigate cultivated area of palm trees. According to recent statistics published by The General Authority for Statistics (2018), approximately 49.7% (58,587 hectares) of the cultivated area uses flood irrigation systems, while 50.3% (59,294 hectare) uses drip irrigation systems, which are recommended to be used to avoid over-exploiting non-renewable groundwater. The estimated amount of water required is 34.73 m^3/tree/year for drip irrigation and 41.99 m^3/tree/year for flood irrigation (Ali et al., 2008) . Assuming that number of palm trees per area is roughly consistent throughout the entire irrigated planted area, number of palm trees per square meter is 0.0218 tree/m^2 (25,640,675/1,178,810,000 m^2). Thus, amount of ground water consumed per drip irrigated area is 0.76 m^3/m^2/year (34.73 m^3/tree/year*0.0218 tree/m^2) and 0.92 m^3/m^2/year (41.99 m^3/tree/year*0.0218 tree/m^2) for flood irrigated area.

- Amount of groundwater= (drip irrigation consummation of ground water, 34.73 m^3/tree)*(palm trees per area, 0.0218 tree/m^2)*(Drip total area, 50.3% * 1,178,810,000 m^2)+ (drip irrigation consummation of ground water, 41.99 m^3/tree)*(palm trees per area, 0.0218 tree/m^2)*(flood total area, 49.7% *1,178,810,000 m^2)= 4.49E+08 m^3+ 5.36E+08 m^3= 9.85E+08 m^3/ yr.
- Density= 1.00E +6 g/m^3 (Essink, 2001).
- Gibbs free energy of groundwater (G): The average dissolved solids in groundwater based on a study conducted in three different wells in Buraydah, Qassim, Saudi Arabia is 992 mg/LITERS (Haider et al., 2020). After conversion to parts per million, S= 933 ppm, where S is solutes in parts per million.

Based on (Odum, 1996, p. 301):

$$\mathrm{G}= \left[\frac{(8.33\frac{J}{mole}/\deg)(300\ C^{\circ})}{19\ g/mole} \right] \mathrm{In} \left[\frac{(1\times10^{6}-S)ppm}{965000} \right] \mathrm{J/g}$$

$$\mathrm{G}= 131.53\ \mathrm{In}\ (999008/965000)$$

$$\mathrm{G}= 4.56\ \mathrm{J/g}$$

Groundwater = (9.85E+08 m^3/yr) * (1.00E+06 g/m^3) * (4.56) = 4.49E+15 J/yr.

Purchased (Imported) resources (IM)

7. Diesel= (volume) * (chemical potential energy per volume).

Due to the data limitation, the volume of diesel used in date farms is estimated based on an aggregated statistic of the whole agricultural production. According to the Agriculture Census 2015) in Saudi Arabia, the total consumption of diesel is 1.83E+09 liters/yr .

- Annual diesel consumed per square meter =0.054 LITERS/m^2/yr (*Agriculture Census*, 2015). The total diesel consumed in the palm tree cultivated area= 0.054 LITERS/m^2/yr* (palm tree cultivated area) 1.18E+09 m^2= 6.37E+07 liters/yr.
- Diesel density = 850 g/LITERS (Speight, 2011).
- Chemical potential energy per volume of Diesel = 5.15E+04 J/g (Jiang et al., 2007).

Diesel = 6.37E+07 LITERS/yr * 850 g/LITERS * 5.15E+04 J/g= 2.79E+15 J/yr.

8. Gasoline= (volume) * (chemical potential energy per volume).

Data from (*Agriculture Census*, 2015; The General Authority for Statistics, 2015) provides an aggregate number of the total consumption of gasoline in agriculture production as 1.76E+07 liters/yr.

- Annual gasoline consumed per square meter= 5.15E-4 LITERS/m^2/yr (*Agriculture Census*, 2015). The total gasoline consumed in the palm tree cultivated area = 5.15E-4 LITERS/m^2/yr*1.18E+09 m^2= 6.07E+05 LITERS/yr.
- Gasoline density= 748.9 g/LITERS (Speight, 2011).
- Chemical potential energy per volume of gasoline= 5.53E+04 J/g (Jiang et al., 2007).

Gasoline= 6.07E+05 LITERS/yr * 748.9 g/LITERS* 5.53E+04 J/g =2.51E+13 J/yr.

9. Machinery= Σ (steel × work hours /economic life/yearly work hours)

Due to the lack of data about the machinery used in date farms, calculations are estimated with reference to the study conducted by Amiri et al. (2021). Data regarding the types of agricultural machinery used in Saudi Arabia are also estimated based on a field study done in Saudi Arabia, in Al-Ahsa city, by The National Center for Palms and Dates (2016).

- Tractor: (Steel weight, 3.60E+06 g * work hours, 20 h/) = 7.20E+11 g*h.
- Carrier tractor trail: (Steel weight, 7.50E+05 g * work hours, 2 h)=1.50E+10 g*h.
- Moldboard plow: (Steel weight, 7.00E+05 g * work hours, 5 h) = 3.50E+10 g*h.
- Disc plow: (Steel weight, 6.00E+05 g * work hours, 1 h) = 6.00E+09 g*h.
- Planter: (Steel weight, 1.00E+06 g * work hours, 1 h) = 1.00E+10 g*h.
- Harrows: (Steel weight, 6.00E+05 g * work hours, 6 h) = 3.60E+10 g*h.
- Chisel plow: (Steel weight, 3.00E+05 g * work hours, 2 h) =6.00E+09 g*h.
- Truck: (Steel weight, 9.00E+06 g * work hours, 2 h) = 1.80E+11 g*h.

Total Σ weight= 1.00 E12 g*h.
Assuming an average economic life of 12 years for agricultural machinery and 540 h/yr.

(Edwards, 2011).

Emergy of machinery= Σ (1.00 E12 g*h /12 yr/ 540 hr/yr) =1.54E+08 g/yr.

10. Fertilizers

Nitrogen N= (volume)*(energy content).

- Volume of Nitrogen=1.28E+03 g / palm tree/ yr (SABIC, 2021) with an energy content of 2.40E+04 J/g (Jiang et al., 2007).

  = (1.28E+03 g/palm/year) *(2.40E+04 J/g)= 3.07E+07 J/yr.

Potash K_2O= (volume)*(energy content).

- Volume of Ptash =1.28E+03 g / palm tree / yr (SABIC, 2021) with an energy content of 9.00E+03 J/g (Jiang et al., 2007).

= (1.00E+03 g/palm/year)*(9.00E+03 J/g)= 9.00E+06 J/yr.

Phosphate P_2O_5 = (volume)*(energy content).

- Volume of Phosphate =6.40E+02 g /palm tree/yr (SABIC, 2021)

Fertilizers are mixed with manure but volume is not determined.

11. Labor ($/yr)

The annual labor cost is estimated to be 11,042.13 $/yr (The National Center for Palms and Dates, 2016). The emergy of labor is based on the national emergy/person/yr which is the emergy to money ratio (Odum, 1996). Emergy to money ratio for Saudi Arabia in 2008 is 6.10E+E12 sej/$ (NEAD, 2008).

Emergy of labor= Labor cost * Emergy/Money ratio for Saudi Arabia in 2008 (NEAD, 2008)

= (11,042.13 $/yr)*(6.10E+12 sej/$)= 6.74E+16 sej/yr.

12. Services

The harsh climate of the Arabian Peninsula places a tremendous challenge on the development of the agricultural sector making it hard to strive without governmental support (Erskine et al., 2004). Accordingly, the Saudi government supports this sector through the Agricultural Development Fund (Agricultural Development Fund, 2019). These funds represent a variety of agricultural aids for farmers within the date industry to assist in financing agricultural-related activities.The funds, for example, include financing agricultural equipment and machinery, as well as facilitating agricultural production marketing processes in both local and international markets. In general, with consideration to differences in agricultural productions in Saudi, the

Agricultural Development Fund finances agricultural investments using two installments' plans. For the first $ 800,000 the fund covers 75% of the expenses, then 50% for more than that with a maximum of $ 5,333,333 for the fund (Agricultural Development Fund, 2019).

With regards to palm trees and dates production, 67% of agricultural funds are directed to dates related productions (Ministry of Environment Water and Agriculture, 2018a). For small size farms, the agricultural fund covers about 10% of their production or around 13 cents per 1kg. The Agricultural Development Fund supports dates production as follows:

- Providing interest-free soft loans for up to $13.3 for each planted tree for eligible farms.
- Offering operations' grants up to 50% of equipment and machinery's cost.
- Covering up to 50% of modern irrigation systems' cost.
- Buying dates crop for incentive prices.
- Free land distribution for palm tree cultivation.

All the above listed forms of agricultural aids represent subsidized services that would greatly affect the Emergy evaluation of the supply chain under study. However, recently, not all services are still granted. For instance, based on communications with experts and farm owners in the region, more restrictions are recently applied to distribution of free land making it very unlikely to be given even for small date producers. Because of the limited published data about land distribution and the recent infrequent application of such support, this type of government fund is not included in this analysis.

In this analysis, two forms of subsidized services will be included, subsidized cost of irrigation systems and agriculture machinery. To test the effect of these subsidized services from a donor-side perspective, a policy will be implemented and tested using SD modeling language, which will be presented in Chapter 6.

Services include the total cost of purchased items per palm tree per year. The cost of purchased services/ resources is based on a field study done in Saudi Arabia, Al-Ahsa city (The National Center for Palms and Dates, 2016).

- Irrigation system= \$0.94/tree/yr. (actual cost of the irrigation system without government subsidy) (The National Center for Palms and Dates, 2016) .

Currently, cost of modern irrigation systems (which include sprinkler, drip, and bubbler systems) for palm plantations are 50% subsidized by the government (Agricultural Development Fund, 2019). Based on The General Authority for Statistics (2018), in aggregate, flood irrigation covers an area of 532,745,000 m^2 , whereas drip irrigation system covers an area of 540,068,000 m^2. Thus, it is reasonable to assume that half of the planted area applies drip irrigation systems making these farms eligible for subsidized prices. The remaining planted area uses conventional irrigation techniques, thus, forced to endure the actual cost of the flood irrigation system without any agricultural funding.

Cost of drip irrigation system per palm tree = (\$0.94/tree/yr, annual cost per tree) *(%50, government subsidy) =\$0.47/tree/yr.

- Cost of flood irrigation system per palm tree = (\$0.94/tree/yr, annual cost per tree) (The National Center for Palms and Dates, 2016)..

In total, the aggregate cost of the irrigation systems for the planted area in Saudi Arabis is:

- Total cost with subsidized irrigation system = (\$17.66/tree/yr * 12,820,338 trees (The General Authority for Statistics, 2020))= \$2.26E+08 per year.
- Total cost without subsidized irrigation system = (\$18.60/tree/yr * 12,820,338 trees (The General Authority for Statistics, 2020)= \$2.38E+08 per year.
- Fertilizers = \$8.28/tree/yr (The National Center for Palms and Dates, 2016).

- Pesticides =$1.73/tree/yr (The National Center for Palms and Dates, 2016).
- Herbicide= $0.96/tree/yr (The National Center for Palms and Dates, 2016).
- Packaging materials= $3.59/tree/yr (The National Center for Palms and Dates, 2016).
- Fuel and other production supplies =$2.63/tree/yr (The National Center for Palms and Dates, 2016).

Total cost per tree with subsidized irrigation system = $17.66/tree/yr.

Total cost per tree without subsidized irrigation system = $18.13/tree/yr.

Other annual expenditures are estimated as follow:

- Machinery and equipment (without government subsidy) =$1,404,480 (The National Center for Palms and Dates, 2016). (50% of machinery cost is subsidized by the government (Agricultural Development Fund, 2019; Aldowaihi, 2020)). After considering government aid for agricultural machinery the total cost is approximately $702,240. The amount of the received fund is subject to eligibility conditions appointed by(Agricultural Development Fund, 2019).
- Capital expenditure= ($845,093 construction work) + ($80,000 vehicles) +($62,667 pre-operating expenses) = $987,760.

Total services cost with government subsidy= 2.26E+08 $/year +2.38E+08 $/year +702,240 $/year + 987,760 $/year = 4.66E+08 $/year.

- The cost of land rent is estimated at $0.70 per square meter with addition to other expenses related to land licenses issuance which is not included in this evaluation (The National Center for Palms and Dates, 2016). The cost of land rent is not included as part of services cost due to data limitations.

- Cost of infrastructure is not considered in this evaluation due to limitations of available data.

The emergy/currency for Saudi equals the total emergy/GDP of a particular year:

In 2014, total emergy of Saudi Arabia= 4.36E+24, the Gross Domestic Product (GDP) in 2014 is $ 6.52E+11 (Source: The National Environmental Accounting Database V2.0).

Thus, the emergy/money ratio = 4.36E+24/6.52E+11= 6.69E+12 sej/$.

Emergy of services= Services Cost * Emergy/Money ratio (NEAD, 2008).

= 4.66E+08 $/yr * 6.69E+12 sej/$ =2.84E+21 sej/yr.

5.2 Emergy Evaluation of Walnut Cultivation

The following section covers the emergy evaluation of the imported walnut shell by-products, which were replaced by date seed by-products as a lost circulation material in Aramco's drilling operations.

Due to data limitations regarding the processes Saudi Aramco applied to walnut shells, and considering that walnut shells are commonly used in drilling operations (Scott and Lummus, 1955), data were estimated from published studies to conduct the emergy evaluation for this section of the research. Most walnuts are imported from California, which is the primary US producer and dominates a large percentage of the global market (Brunke, 2004). According to Azubike et al. (2019), to transform walnut shells into lost circulation material, four simple processes are performed. First, the walnut shells are cleaned. Then they are dried at 60°C (140 °F) for 3–4 hours. Next, the dried walnut shells by-products are ground. Finally, the ground material is sieved to separate desired particle size.

Historical data is used to determine a realistic estimation of the quantity of walnut shells that Aramco imported from the United States. Based on Barbu et al. (2020), walnut shells comprise67% of the walnut produced. Thus, given that the 2018 production of walnut in California was 676,000 tons (USDA, 2020b), walnut shell by-products amount to approximately 452,920 tons.

Table 5-2 outlines all renewable (R), non-renewable (N), and purchased resources (IM) as well as the L&S required to produce walnuts in US. The first column, "item," represents the resources included in the evaluation. The second column, "raw amount," is the available energy within each resource. The third column shows the unit used for each resource. The fourth column is the UEV for each resource, which represents all the previous environmental activities that have taken place to produce each resource. UEVs are derived from previous studies, which are referenced in the fifth column. Finally, the sixth column presents the emergy value of each resource flowing into the system after conversion.

Table 5-2: Emergy Evaluation of Walnut Cultivation in the United States

Item	Raw amount	Unit	UEV (sej/unit)	Reference of UEV	Emergy flows (sej/yr)
Local renewable resources (R)					
Primary renewable flows					
1. Solar radiation	1.61E+19	J	1	(Odum, 1996)	1.61E+19
2. Geothermal heat	4.08E+13	J	4.90E+03	(Brown and Ulgiati, 2016)	2.00E+17
Sum of primary flows					1.63E+19
Secondary renewable flows					
3. Rain (chemical potential)	3.11E+15	J	7.00E+03	(Brown and Ulgiati, 2016)	2.18E+ 19
4. Wind	2.36E+16	J	8.00E+02	(Brown and Ulgiati, 2016)	1.88E+19
Max of secondary flows					2.18E+ 19
Subtotal					3.81E+19
Local non-renewable resources (N)					

5. Soil loss (organic matter)	1.49E+13	J	7.40E+04	(Odum, 1996)	1.10E+18
6. Groundwater	4.73E+15	J	4.10E+04	(Odum et al., 1995)	1.94E+20
Subtotal					1.95E+20
Purchased (imported) resources (IM)					
7. Diesel	1.18E+15	J	6.60E+04	(Odum, 1996)	7.78E+19
8. Gasoline	1.13E+15	J	6.60E+04	(Odum, 1996)	7.49E+19
9. Machinery	4.00E+03	g	6.70E+09	(Arding and Brown, 1991)	2.68E+13
10. Fertilizers					
Nitrogen (N)	2.88E+05	J	1.69E+06	(Odum, 1996)	4.88E+11
Subtotal					1.53E+20
Labor and Services (L&S)					
11. Labor (L)	1.13E+05	$/yr	--	(NEAD, 2008)	4.20E+17
12. Services (S)	4.39E+06	$/yr	--	(NEAD, 2008)	1.10E+19
Subtotal					1.14E+19
Total Emergy with L&S					3.97E+20
Total Emergy without L&S					3.86E+20
Walnuts' mass	6.76E+11	g	--	(USDA, 2020b)	--
percent of generated walnut shells byproduct	67%	g	--	(Barbu et al., 2020)	--
Energy content*	1.47E+16	J	--	--	--
Specific emergy (with L&S)[1]	--	sej/g	5.87E+08	This study	--
Specific emergy (without L&S)[2]	--	sej/g	5.71E+08	This study	
UEV of walnut shells (byproduct)[3]	--	sej/g	3.83E+08	This study	
UEV with L&S[4]	--	sej/J	2.70E+04	This study	--
UEV without L&S[5]	--	sej/J	2.63E+04	This study	--

Units are defined in the appendix, Table 10-1.

*Energy content per gram of walnuts is 2.18E+04 J(Baer et al., 2016). For the mass of walnuts produced, the energy content is 1.47E+16.

[1] Specific walnut emergy (with L&S) = Total emergy (with L&S) 3.97E+20/ Walnut's mas6.76E+11.

[2] Specific walnut emergy (without L&S) = Total emergy (without L&S) 3.86E+20/ walnuts' mas6.76E+11.

[3] UEV of walnut shells (byproduct)= Specific walnut emergy (without L&S) 5.71E+08* 67% of generated reusable walnut shells.

[4] UEV with labor and services= Total emergy (with L&S) 3.97E+20/ Energy conten47E+16.

[5] UEV without labor and services= Total emergy (without L&S) 3.86E+20/ Energy content 1.47E+16.

Emergy calculations of the walnut production in the Uni States:

1. Solar energy (J) = (Cultivated area)*(Insolation)*(1-Albedo).

- Cultivated area= total planted area of bearing walnut trees in California is 1.68E+09 m^2 (USDA, 2020a).
- Insolation= average hours of sunshine = 3.25E+3 h/yr (Information, 2021)* 3.60E+6 ($J/m^2/yr$)= 1.17E+10 $J/m^2/yr$.
- Albedo= 0.18 (Li, 2015, p. 63).

Solar energy (J) = (1.68E+09 m^2)*(1.17 E+10 $J/m^2/yr$.)*(1-0.18)= 1.61E+19 J/yr.

2. Geothermal Heat Energy (J**)** = (Cultivated area) *(Heat flow per area)*(Carnot efficiency).

- Cultivated area= 1.68E+09 m^2.
- Heat flow per area = 2.56E+05 $J/m^2/yr$ (Garai et al., 2010).
- Carnot efficiency= 9.5% (Brown and Ulgiati, 2016).

Geothermal Heat Energy (J) =(1.68E+09 m^2) *(2.56E+05 $J/m^2/yr$)* (9.5%)= 4.08E+13 J/yr.

3. Rain, chemical potential energy (J) = (Cultivated area)*(Rainfall)*(Transpiration rate)*(Water density)*(Gibbs energy of rain).

- Area= 1.68E+09 m^2.
- Rainfall per year= 1.1176 m/yr ("UC Drought Management ")
- Transpiration rate= estimated at 35% (Burt et al., 2001; Fulton and Buchner, 2015)
- Water density= 1000 kg/m^3.
- Gibbs energy of rain = 4.72J/g, (Brown and Ulgiati, 2018).

Rain, chemical potential energy (J) = (1.68E+09 m^2) *(1.12 m/yr)*(0.35)* (1.00E+06 g/m^3)*(4.72J/g) = 3.11E J/yr.

4. Wind energy (J) = (Cultivated area)* (Air density) *(Drag coefficient) *(Geostrophic wind velocity) ^3.

- Cultivated area= 1.68E+09 m^2.
- Air density= 1.23 kg/m^3.
- Drag coefficient = 1.64E-03 (Garratt, 1994).
- Geostrophic wind velocity = Annual average wind speed/0.6 = 3.62/0.6 m/s = 6.04 m/s ("Walnut Wind Forecast,").

Wind energy (J)= (1.68E+09 m^2) *(1.23 kg/m^3)*(1.64E-03)*(6.04 m/s)^3*(3.154E+07 s/yr) = 2.316 J/yr.

5. Soil loss (organic matter):

Net loss of topsoil = (Cultivated area) *(Erosion rate).

- Cultivated area= 1.68E+09 m^2.

The energy of soil used, or lost = (Net loss topsoil) *(% Organic matter) *(5.4 kcal/g)*(4186 J/kcal).

- The average annual soil erosion in California is calculated using the Universal Soil Loss Equation (USLE) model and estimated to be 11.21 g/m^2/yr (Salls et al., 2018).
- % organic matter= 3.5% (Ponder, 2004).

= (1.68E+09 m^2) *(11.21 g/m^2/yr) *(3.5%) *(5.4 kcal/g) *(4186 J/kcal) = 1.49E+13.

6. Groundwater = (Water volume) * (Density) * (Gibbs free energy)

- Water volume= 6096 m^3/hectare/yr (Sears et al., 2019). For the total bearing area of walnuts (167,945 hectare), the total amount of water used is 1.02E+09 m^3/yr.
- Density= 1000 kg/m^3 or 1.00E+06 g/m^3 (Essink, 2001).
- Gibbs free energy of groundwater (G):

The threshold of total dissolved solids (TDS) in groundwater in California for agricultural use only is set between 700 mg/liters TDS and 2000 mg/LTDS (Kang et al., 2020; Luciuk et al., 2000). Since an exact value of TDS in groundwater used for irrigation is not available an estimated value is used based on a study conducted by Kent and Landon (2013). The study stated that 67% of wells have moderate TDS concentrations between 250 mg/LITERS and 500 mg/LITERS ($> 250 \leq 500$). Thus, the estimated TDS value used in this study is 500 mg/LITERS. After conversion to parts per million, S= 500 ppm, where S is solutes in parts per million.

Based on (Odum, 1996, p. 301):

$$G= [\frac{(8.33\frac{J}{mole}/deg)(300\ C°)}{19\ g/mole}]In [\frac{(1\times10^{6}-S)ppm}{965000}]\ J/g$$

$$G= 131.53\ In\ (999{,}500/965{,}000)$$

$$G= 4.62$$

Groundwater = (1.02E+09 m^3/yr.) * (1.00E+06 g/m^3) * (4.62) = 4.73E+ 15 J/yr.

The irrigation method is micro sprinkler with one sprinkler per tree and an average hourly water application rate of 0.076 inch per hour.

7. Diesel= (volume) * (chemical potential energy per volume).

- Annual diesel consumed per square meter= 0.0160 LITERS/m^2/yr (VALLEY, 2006), total consumed for walnut product= 0.0160 LITERS/m^2/yr * (walnut cultivated area) 1.68E+09 m^2 = 2.69E+07 LITERS/yr.
- Diesel density 850 g/LITERS (Speight, 2011).
- Chemical potential energy per volume of Diesel = 5.15E+04 J/g (Jiang et al., 2007).

Diesel = 2.69E+07 LITERS/yr* 850 g/LITERS* 5.15E+04 J/g= 1.18E+15 J/yr.

8. Gasoline= (volume) * (chemical potential energy per volume).

- Annual gasoline consumed per square meter= 0.0163 LITERS/m^2/yr * (walnut cultivated area) 1.68E+09 m^2 = 2.74E+07 LITERS/yr (VALLEY, 2006).
- Gasoline density= 748.9 g/LITERS (Speight, 2011).

- Chemical potential energy per volume of gasoline= 5.53E+04 J/g (Jiang et al., 2007).

Gasoline= 2.74E+07 LITERS/yr *748.9 g/LITERS * 5.53E+04 J/g = 1.13E+15 J/yr.

9. Machinery

Types of Machinery and working hours are estimated from (Buchner et al., 2002; Krueger et al., 2012).

- Two-Wheel Drive Tractor: (Steel weight, 2.29E+06 g * work hours, 3 h^r) = 6.87E+06 g/hr/m^2.
- Mechanical Front-Wheel Drive Tractor: (Steel weight, 2.69E+06 g (Yumpu.com) * work hours, 3 hr/m^2) = 8.10E+06 g*hr/m^2.
- All-terrain vehicle (ATV) :(Steel weight, 2.68E+05 g * work hours, 0.62 hr/m^2) = 1.66E+05 g*hr/m^2.
- Mower-Flail :(Steel weight, 4.70E+05 g (Yumpu.com) * work hours, 0.55 hr/m^2) = 2.59E+05 g*hr/m^2.
- Orchard Sprayer :(Steel weight, 8.00E+05 g (Munchhof)* work hours, 0.59 hr/m^2) = 4.72E+05 g*hr/m^2.
- Pickup truck:(Steel weight, 4.54E+06 g (Howstuffworks)* work hours, 0.55 hr/m^2) = 2.49E+06 g*hr/m^2.
- Loader Fork:(Steel weight, 1.95E+05 g (Caterpillar)* work hours, 0.36 hr/m^2) = 7.01E+04 g*hr/m^2.

Total Σ wight = 1.84E+07 g*hr/m^2.

Assume an average economic life of 13 years for agricultural machinery and 354 annual operating hours (Edwards, 2011; Krueger et al., 2012).

Emergy of machinery= Σ (1.84E+07 g*hr/m^2 /13 yr/354 hr/yr) = 4.00E+03 g/ m^2.

10. Fertilizers:

- Nitrogen N= (Volume)*(Energy Content).

Volume of Nitrogen: according to Krueger et al. (2012), the averge amount of annual fertilizer application is about 12 $g/m^2/yr$.

- Energy content of 2.40E+04 J/g (Jiang et al., 2007).

Nitrogen N= (12 $g/m^2/yr$)*(2.40E+04) = 2.88E+05 J.

- Potassium Potash (K_2O) = (Volume)*(Energy Content)
- Volume of Potassium: 6.73 $g/m^2/yr$ (Hasey et al., 2018).
- Energy content of 9.00E+03 J/g (Jiang et al., 2007).

Potassium Potash (K_2O) = (6.73 $g/m^2/yr$) *(9.00E+03 J/g)= 6.06E+05 J.

11. labor (J/h/yr):

- The average labor cost per hour to produce walnut is $19.17($20.59 for a machine operating labor and 17.75 for non-machine operating labor) (Hasey et al., 2018).
- The estimated annual labor cost is 19.17 $/hr *8765.82 hr/yr= 168,041 $/yr.
- The emergy of labor is based on the national emergy/person/yr which is the emergy to money ratio(Odum, 1996).

Emergy to money ratio for the United States in 2008 is 2.50E+12 sej/$ (NEAD, 2008).

Emergy of labor= Labor cost * Emergy/Money ratio

= (1.68E+05 $/yr) *(2.50E+12 sej/$)

= 4.20E+17 sej/yr

12. Services ($/yr):

Services are evaluated in terms of their annual cost as follows:

Fertilizers:

According to a study conducted in 2012 (Krueger et al., 2012) , the total annual fertilizer cost per acre is $136. In 2012, the average number of bearing walnut trees per one acre of land is 68.6 with a total planted total of 270,000 bearing acres (USDA, 2020b). Thus, to get a realistic estimation of the annual fertilizer cost of walnut trees the annual cost per acre is divided by the number of trees per acre ($136 per acre/ 68.6 tree per acre ≈ 2 $/tree/yr).

Fertilizer cost= $2/tree/yr.

Irrigation system:

The irrigation system evaluated for walnut plantation is sprinkler irrigation method and it costs $124 /year/acre (Hasey et al., 2018). Considering that one acre of walnut orchard contains about 68.6 trees (USDA, 2020b), the cost of irrigation method per tree is $1.80 /tree/yr ($124 per acre / 68.6 tree per acre).

Pesticides= $3.59/tree/yr ($246 per acre/ 68.6 tree per acre) (Hasey et al., 2018).

Herbicide= $1.24/tree/yr ($85 per acre/68.6 tree per acre) (Hasey et al., 2018).

Diesel= $0.77/ liters ($2.92 per gallon/ 3.79 liters per gallons) (Hasey et al., 2018).

Gasoline= $0.91/ liters ($3.46 per gallon/ 3.79 liters per gallons) (Hasey et al., 2018).

Machinery and equipment = $269,263 (Hasey et al., 2018).

Capital expenditure= $4,123,000 (Hasey et al., 2018).

Total services cost= $ 4,392,273.

Emergy to money ratio for the United States in 2008 is 2.50E+12 sej/$ (NEAD, 2008).

Emergy of services= services cost * Emergy/Money ratio

= $ 4,392,273 * 2.50E+12 sej/$ = 1.10E+19 sej/yr.

5.3 Emergy Evaluation of Transportation System

The transportation system in the date seed supply chain is relatively different from that of the walnut shell supply chain in terms of downstream activities. An initial conjecture in this research is that transportation may be a discriminator between the two approaches when considering their emergy profiles and outcomes.

In this research, the date seed by-product supply chain represents a local circular economy (CE) supply chain in Saudi Arabia and supplies a local company within similar geographical boundaries. By contrast, the walnut shell supply chain extends overseas and represents a global supply chain supplying a foreign market. To calculate the emergy of the transportation section, several assumptions are made to overcome data limitations. Considering that the date seed by-product supply chain is local, only road transportation is assumed. For the walnut shells, combined transportation modes are assumed to facilitate activities of such a global supply chain. Thus, walnut shell by-products are transported via road and maritime shipping. Figure 5-3 summarizes all modes of transportation for date seeds and walnut shells.

Given the data limitation for modeling the two supply chains, some values of the two transportation systems are standardized. More precisely, to make a comparative assessment of the transportation system used in delivering the date seeds and walnut shells to the same final destination, the same values are estimated regarding the distance from the farm to the processing factory, and from the factory to Aramco's facility. The differences between the two transportation systems will be noted with other inputs to these systems. In other words, fuel prices, cost of labor, distance traveled outside Saudi Arabia, and cost of services will differ in the two investigated supply chains.

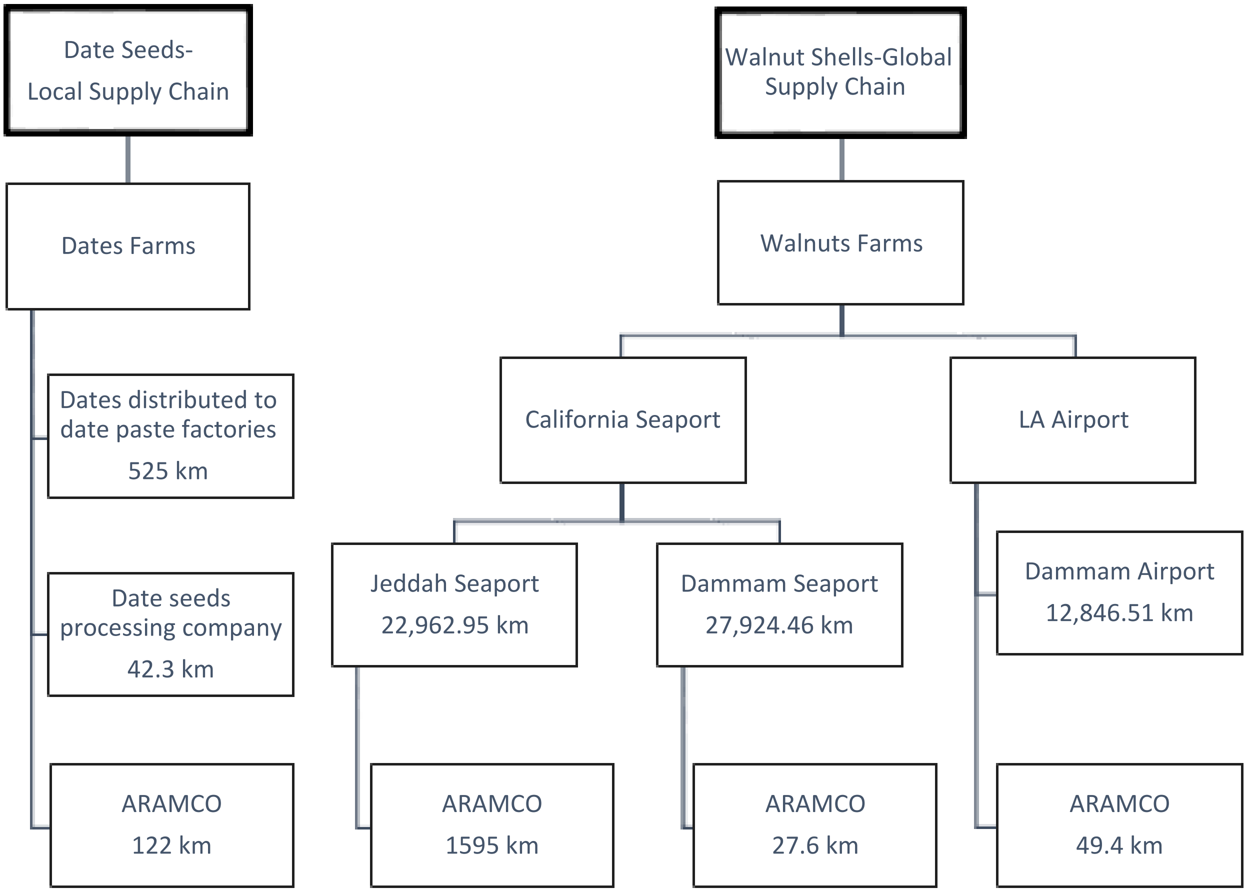


Figure 5-3: Transportation System Flowchart for the Investigated Supply Chains

5.3.1 Date Seed Transportation

For the transportation system of the distribution of date seeds in Saudi Arabia, only road transportation by trucks is assumed because it is part of a local supply chain, and all logistical activities are performed within the same geographical boundary. The flowchart in Figure 5-4 illustrates the specific structure of the date seed by-product supply chain. All the agricultural activities take place within the first stage of the investigated supply chain, which ends with harvesting the raw dates from local farms. Raw dates are then distributed to various destinations including wholesale and retail markets, date factories, exports, and date transformative factories; the latter represents the originating source of the seeds in this study.

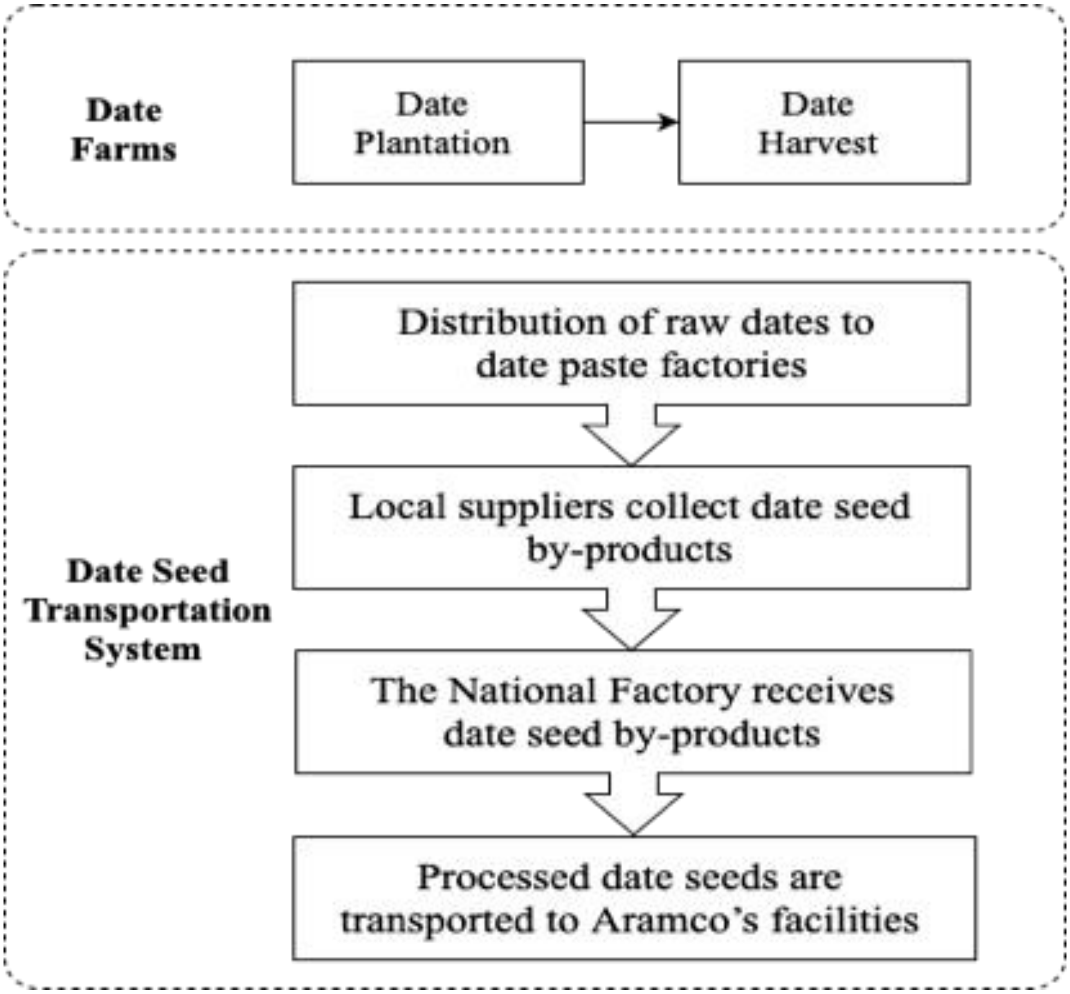


Figure 5-4: Date Seed By-products Supply Chain Flowchart

Due to the absence of some data on the transportation system, estimations of the distance, machinery, labor, and services are made to give an approximate emergy assessment of the investigated system. The transportation system is evaluated using emergy based on multiple stages as follows:

- The transportation system for date seeds starts from date farms located within Saudi Arabia. Harvested dates are transferred from date farms to date paste transformative factories, where date seeds are generated as waste. The distance from date farms to date paste factories is estimated according to a study by Price Waterhouse Coopers (2019).

- Due to the high demand for date seeds in the market, date seeds are collected from multiple factories that are geographically dispersed around the country. Thus, one data limitation is that the exact source of date seeds cannot be conclusively determined. As a result, a large-scale date paste factory is used as a generic example to estimate distance from the date paste factory to the date seed factory. Al-Ahsa Food Industries Company is used for two reasons. First, the company is located in Eastern Province, where Aramco as well as the date seed by-product processing factory are located. Second, personal communications with experts in the industry confirm that the factory runs a large-scale production, which indicates the amount of generated date seed waste that can be sold in a secondary market. The factory is located at CJ73+53 Al Mubarraz, approximately 42.3 km from the National Factory, where the date seeds are processed.
- Date paste factory waste is then transferred to a secondary market in which its by-products are used by various industries—in this case, well drilling operations. The date seed by-products are transported to the National Factory in Al-Ahsa, Saudi Arabia, to undergo the six processes.
- The final destination of the processed date seeds is Aramco’s facilities. The distance between the date seed processing factory (National Factory) and Aramco is approximately 122 km.

Table 5-3 represents an estimate of the emergy evaluation of road transportation to transfer dates from farms to date paste transformative factories. The first column, “item,” represents the resources included in the evaluation. The second column, “raw amount,” is the available energy within each resource. The third column shows the unit used for each resource. The fourth column is the UEV for each resource, which represents all the previous environmental activities that have taken place to produce each resource. UEVs are used from previous studies, which are referenced in the fifth column. Finally, the sixth column presents the emergy value of each resource flowing into the system after conversion.

Table 5-3: Emergy Evaluation of the Date Seeds Transportation System

Item	Raw Amount	Unit	UEV (sej/unit)	Reference of UEV	Emergy Flows (sej/yr)
Purchased (Imported) resources (IM)					
Purchased Date seeds[1]	3.88E+08	g	4.25E+07	This study	1.65E+16
Road transportation					
1. Diesel fuel	1.32E+11	J	6.60E+04	(Odum, 1996)	8.71E+15
2. Machinery	9.37E+02	g	6.70E+09	(Arding and Brown, 1991)	6.28E+12
3. Labor	1.60E+04	$/yr	--	(NEAD, 2008)	9.76E+16
4. Services	6.72E+04	$/yr	--	(NEAD, 2008)	4.10E+17
Total Emergy with L&S					5.17E+17
Total Emergy (without L&S)					2.52E+16
Transported date seeds	3.88E+08	g	--	Estimated	--
Energy content*	4.77E+12	J	--	This study	--
Specific emergy (with L&S)[2]	--	sej/g	1.33E+09	This study	--
Specific emergy (without L&S)[3]	--	sej/g	6.49E+07	This study	--
UEV with L&S[4]	--	sej/j	1.08E+05	This study	--
UEV without L&S[5]	--	sej/J	5.28E+03	This study	--

Units are defined in the appendix, Table 10-1.

*Energy content per gram of date seeds is 1.23E+04 J(Kamel et al., 1981). For the mass of date seeds produced, the energy content is 3.88E+08 *1.23E+04 =4.77E+12.

[1] UEV of non-transported date seeds= Specific dates emergy (without L&S) 2.83E+08* 15% percent of generated reusable date seeds.

[2] Specific emergy (with L&S)= Total emergy (with L&S) 1.19E+18/ transported date seed3.88E+08.

[3] Specific emergy (without L&S)= Total emergy (without L&S) 1.65E+16/ transported date seeds 3.88E+08.

[4]UEV with labor and services= Total emergy (with L&S) 1.19E+18/ Energy conten3.54E+12.

[5] UEV without labor and services= Total emergy (without L&S) 1.65E+16/ Energy content 3.54E+12.

1. Diesel fuel

The distance traveled from date farms to date transformative factories is estimated according to a field study published by Price Waterhouse Coopers (2019). Date seeds used in Aramco’s drilling operations are agricultural waste generated from date transformative factories located in different regions and cities around Saudi Arabia. The seeds are extracted from raw dates, which come from multiple sources (farms); then the contracting factory, the National Factory in Al-Ahsa, collects the date seeds from a local supplier. Because data about the different stages of the date seed handling and shipping is not available, assumptions are made about the traveled distances and modes of transportation used.

According to Price Waterhouse Coopers (2019), the distance from date farms in the region to date transformative factories is estimated at approximately 50 km for small farms that cannot afford refrigerated trucks and between 50–1000 km for large-scale date farms that use refrigerated trucks to prevent damage by high temperatures. An average of 525 km is used as a middle value to estimate the emergy of the total fuel consumed during the delivery of the date seeds.

The date seeds are generated as waste from date paste factories and collected by suppliers to be sold in a secondary market. As an example, a date paste factory is used as a reference to estimate the distance to the date seed processing company, the National Factory. Distance from the date paste factory, Al-Ahsa Food Industries Company, to the National Factory in Al-Ahsa, is estimated at 42.3 km. Moreover, it is assumed that date waste is delivered using non-refrigerated trucks.

The final destination of the processed date seeds is Aramco’s labs in the EXPEC Advanced Research Center located at 847H+27 Dhahran. The distance between the two locations is determined using Google Maps as shown in the Figure 5-5 below. This distance is 106–138 km (122 km is used as an average distance) depending on the road taken.

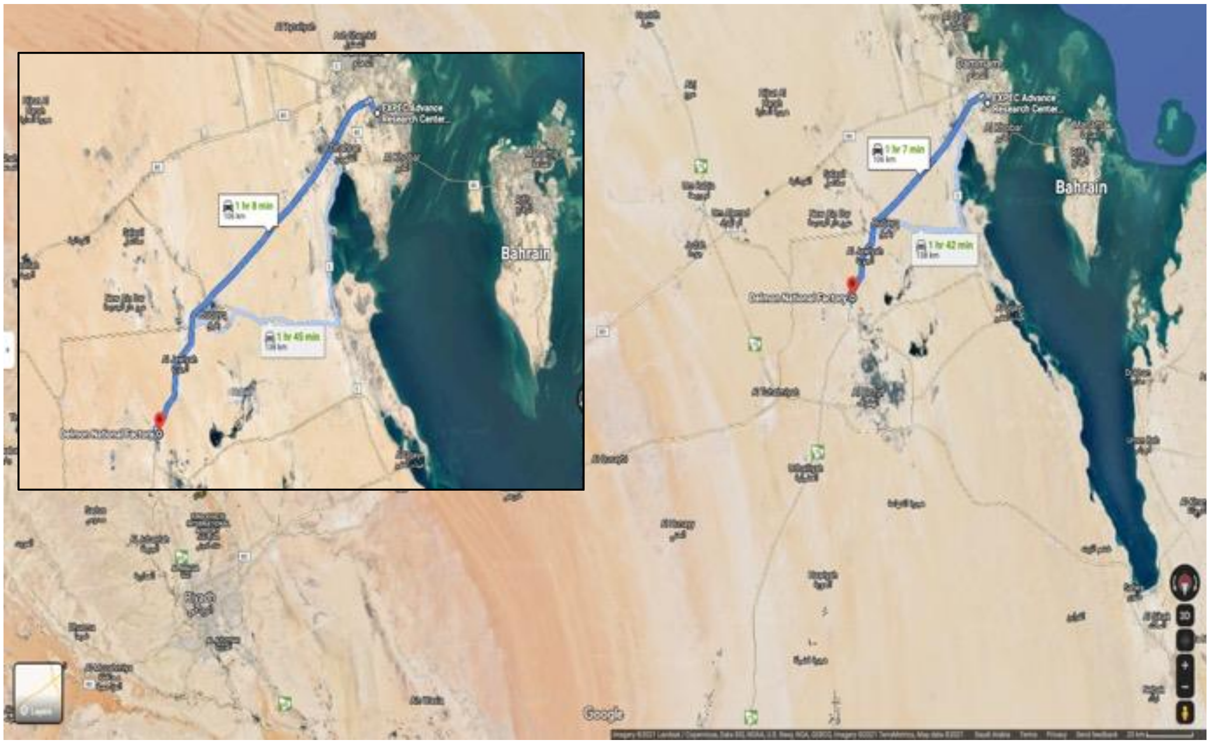


Figure 5-5: Snapshot of the Distance between Date Seeds Processing Factory and Aramco's Labs

- It is assumed that deliveries from date farms to date factories are done by refrigerated trucks to maintain freshness of the raw dates, whereas deliveries of date seeds from the manufacturing company to Aramco's facility are done by non-refrigerated trucks.
- According to Dua and Sheldon (2019), the average distance traveled per liter of diesel for non-refrigerated light-duty trucks is 8.93 km/LITERS. Refrigerated trucks travel approximately 2.95 km/LITERS on average (Gaines et al., 2006).
- Chemical potential energy per volume of diesel is 5.15E+04 J/g (Jiang et al., 2007).
- Diesel density = 850 g/LITERS (Speight, 2011).

- Emergy of diesel = (average diesel consumed per km for deliveries from date farms to date factories using refrigerated trucks * traveled distance + average diesel consumed per km for deliveries from the date paste factory to date seeds processing factory using non-refrigerated trucks * traveled distance + average diesel consumed per km for deliveries from the date seeds processing factory to Aramco’s facility using non-refrigerated trucks * traveled distance) * (chemical potential energy per volume).

Diesel consumed = (2.95 LITERS/km * 525 km +8.93 LITERS/km * 42.3 km+ 8.93 LITERS/km *122 km) * *850 g/LITERS *5.15E+04 J/g = 1.32E+11 J.

2. Machinery

Machinery= Σ (Steel weight × work hours /economic life/yearly work hours)

- A light-duty truck can weigh up to 2,722,008 g while a mid-size refrigerated truck weighs around 11,339,809g (Gaines et al., 2006).
- Working hours are estimated at 6000 hours/year (Institute, 1986), and 8 hours/day according to the Saudi Transport General Authority regulations.
- Average economic life of 20 years based on regulations by the Saudi Transport General Authority.

machinery= (2,722,008g + 11,339,809g) × 8 hrs /20 yr/6000 hr/yr) = 937.45 g.

3. Labor ($/yr)

Emergy of labor= Labor cost * Emergy/Money ratio for Saudi Arabia in 2008 (NEAD, 2008).

According to the Career Education and Development, truckers’ monthly wage is between $800-$1866 which equate to an average of $16000 annually.

Emergy of labor= $1.60E+04 * 6.10E+12 sej/$= 9.76E+16 sej/yr.

4. Services

Due to the absence of detailed data about the services associated with distribution of dates and dates seeds, only trucks and fuel costs are considered as services.

Emergy of services= Services cost * Emergy/Money ratio for Saudi Arabia in 2008 (NEAD, 2008).

Services costs are estimated from previous studies as follow:

- Refrigerated trucks: $4.00E+04 (The National Center for Palms and Dates, 2016).
- Light- duty trucks: $2.67E+04 (The National Center for Palms and Dates, 2016).
- Diesel prices in Saudi Arabia is 0.14 USD per liter (based on Aramco's published rates).
- Assuming that a refrigerated light-duty truck travels about 525 km for deliveries from date farms to date paste factories with a rate of 2.95 km/liters (Gaines et al., 2006). Also, assuming that a non-refrigerated truck travels about 42.3 km from date paste factories to the date seeds processing factory , and travels 221 km to transfer processes date seeds from the date seeds processing factory to Aramco's facility with a rate of 8.93 km/liter (Dua and Sheldon, 2019).

Diesel cost= ($0.14 per liter * 2.95 km/liters*525 km) +($0.14 per liter*8.93 km/liter* 42.3 km) + ($0.14 per liter*8.93 km/liter* 221 km) = $546.

Total services cost= $4.00E+04 + $2.67E+04 + $546 = $6.72E+04 $/yr.

Emergy of services= Services cost * Emergy/Money ratio for Saudi Arabia in 2008 (NEAD, 2008).

= $6.72E+04* 6.10E+12 sej/$=4.10E+17 sej/yr.

5.3.2 Walnut Shells Transportation

The data used in this section is taken from previous studies and official government reports to estimate values of cargo mileage and fuel consumption in transportation of agricultural products in California. For deliveries of walnuts from farms to factories, the same estimated distance used in dates deliveries from farms to factories are used.

- Assuming that deliveries from walnut farms to factories are made using refrigerated trucks with an average traveled distance of 2.95 km/LITERS of diesel consumed (Gaines et al., 2006).
- The walnut shells are generated as agricultural waste from walnut processing factories in California (Pujol Pereira et al., 2016). Due to the absence of data on the exact location from which walnut shells are generated and shipped, this study assumes that Aramco imports unprocessed shells directly from walnut factories in California, estimating distance using figures from previous studies. Traveled distance is estimated based on a report published by Gerald and Dorothy (2019), which measured the distance between walnut acreage and major ports in California. The report states that approximately 82.5% of walnut acreage is between 0 and 150 miles from major seaports; hence, an average distance of 120.7 km (75 miles) will be used for shipments of walnut shells from walnut factories to major California seaports. Furthermore, it is assumed that walnut shells are delivered from factories to seaports located within the same radius using non-refrigerated trucks with fuel consumption of approximately 8.93 km/liter (Dua and Sheldon, 2019).
- Average distance from California seaports to Saudi seaports is estimated assuming that the shipment originates from the San Francisco seaport (USSFO) located at QJW4+5J South Beach, San Francisco, CA, USA to Dammam seaport (DMM) located at F55Q+M2 Dammam, KSA. The distance between the origin point to the destination of shipment varies depending on transportation mode.

- According to Willow Oak Group the average distance traveled per unit of fuel is approximately 244.9 km/LITERS for cargo ships and 1.91 km/LITERS for airplanes, assuming an average cargo load and speed depending on the type of transportation.

Table 5-4 represents the emergy evaluation of all modes of transportations used to import walnut shells from the US to Saudi Arabia. The first column, "item," represents the resources included in the evaluation. The second column, "raw amount," is the available energy within each resource. The third column shows the unit used for each resource. The fourth column is the UEV for each resource, which represents all the previous environmental activities that have taken place to produce each resource. UEVs are used from previous studies, which are referenced in the fifth column. Finally, the sixth column presents the emergy value of each resource flowing into the system after conversion.

Table 5-4: Emergy Evaluation of the Walnut Shells Transportation System

Item	Raw Amount	Unit	UEV (sej/unit)	Reference of UEV	Emergy flows (sej/yr)
Purchased (Imported) resources (IM)					
Walnut shells	3.88E+08[1]	g	3.83E+08[2]	This study	1.45E+17
By sea					
1. Diesel fuel for route 1	2.90E+11	J	6.60E+04	(Odum, 1996)	1.92E+16
2. Diesel fuel for route 2	3.52E+11	J	6.60E+04	(Odum, 1996)	2.32E+16
3. Machinery	7.28E+07	J	6.70E+09	(Arding and Brown, 1991)	4.87E+17
4. Labor	4.98E+04	$/yr	--	(NEAD, 2008)	1.25E+17
5. Services route 1	3.88E+06	$/yr	--	(NEAD, 2008)	9.70E+18
6. Services route 2	4.50E+06	$/yr	--	(NEAD, 2008)	1.13E+19
Total Emergy of route 1 (with L& S)					**1.05E+19**
Total Emergy of route 1 (without L& S)					**6.51E+17**
Total Emergy of route 2 (with L& S)					**6.83E+20**
Total Emergy of route 2 (without L& S)					**1.21E+19**
By air					
7. Diesel fuel	1.34E+09	J	6.60E+04	(Odum, 1996)	8.86E+13

8. Machinery	7.84E+05	J	6.70E+09	(Arding and Brown, 1991)	5.25E+15
9. Labor	4.98E+04	$/yr	--	(NEAD, 2008)	1.25E+17
10. Services	3.04E+06	$/yr	--	(NEAD, 2008)	7.60E+18
Total Emergy (with L&S)					7.90E+18
Total Emergy (without L&S)					1.50E+17
Transported walnut shells	3.88E+08	g	--	Estimated	--
Energy content*	7.53E+12	J	--	This study	--
Emergy for sea cargo (route1)					
Specific emergy (with L&S)[3]	--	sej/g	2.21E+10	This study	--
Specific emergy (without L&S)[4]	--	sej/g	1.68E+09	This study	--
UEV with L&S[5]	--	sej/J	1.39E+06	This study	--
UEV without L&S[6]	--	sej/J	8.65E+04	This study	--
Emergy for sea cargo (route2)					
Specific emergy (with L&S)	--	sej/g	1.76E+12	This study	--
Specific emergy (without L&S)	--	sej/g	3.12E+10	This study	--
UEV with L&S	--	sej/J	9.09E+07	This study	--
UEV without L&S	--	sej/J	1.61E+06	This study	--
Emergy for air cargo					
Specific emergy (with L&S)	--	sej/g	2.04E+10	This study	--
Specific emergy (without L&S)	--	sej/g	3.87E+08	This study	--
UEV with L&S	--	sej/J	1.05E+06	This study	--
UEV without L&S	--	sej/J	1.99E+04	This study	--

Units are defined in the appendix, Table 10-1.

*Energy content per gram of walnut shells is 1.92E+04 J (Onay et al., 2004).For the mass of walnut shells, the energy content is 3.88E+08*1.92E+04 =7.53E+12.

[1] The volume of walnut shells is assumed to be equal to the volume of date seeds trported.

[2] UEV of non-transported walnut shells= Specific walnut emergy (without L&S) 3.83E+08* 67% of generated reusable walt shells.

[3] Specific emergy for route 1 (with L&S) = Total emergy (with L&S) 1.05E+19/ transported walnut shells 3.88E+08g.

[4] Specific walnut emergy for route 1 (without L&S) = Total emergy (without L&S) 6.51E+17/ transported walnut shells 3.88E+08g.

[5] Rout 1 UEV (L&S) = Total emergy (with L&S) 1.05E+19/ Energy content 7.53E+12.

[6] UEV of walnut shells (route 1)= walnut total emergy (without L&S) 6.51E+17/ Energy content 7.53E+12.

The Emergy of Fuel: the amount of fuel consumed is estimated for deliveries made outside the walnut farms in California, United States.

Sea cargo

Route 1:

- From San Francisco Seaport to Jeddah Islamic Seaport the distance is 12,399 Nautical mile (about 22,962.948 km) estimated according to Port.com
- Shells are then shipped via road to ARAMCO’s facility to the eastern province in Dammam travelling approximately 1,595 km (estimated using Google Maps).

Route 2:

- Another route is from san Francisco Seaport to King Abdul Aziz Port in Dammam the distance is 15,078 Nautical mile (about 27,924.456 km) (estimated using Ports.com).
- Then shells are shipped via road to ARAMCO’s facility travelling approximately 27.6 km) (estimated using Google Maps).

Air cargo

- Assuming the that 120.7 km is the average traveled distance from walnuts farms to Los Angeles International Airport.
- From Los Angeles International Airport to King Fahd Airport in Dammam the distance is 12,846.51 km (Prokeraia.com).
- Then shells are shipped via road to ARAMCO’s facility travelling approximately 49.4 km) (estimated using Google Maps).
- Chemical potential energy per volume of diesel is 5.15E+04 J/g (Jiang et al., 2007).

The emergy evaluation of all possible transportation modes is detailed below in the same order as shown in Table 5-4.

Emergy of diesel for sea cargo

1. Diesel for Route 1 (California seaport → Jeddah seaport)

= (average diesel consumed per km for deliveries from walnut farms to the California seaport using non-refrigerated trucks * traveled distance + average diesel consumed per km for shipping walnut shells from the California seaport, USA, to the Jeddah seaport, KSA * traveled distance + average diesel consumed per km for deliveries from the Jeddah seaport, KSA, to Aramco's facility using non-refrigerated trucks * traveled distance) * (chemical potential energy per volume).

= (8.93 km/liter * 120.7 km + 244.9 km/liter *22,962.95 km +8.93 km/liter * 1,595 km) * (5.15E+04 J/g)= 2.90E+11 J.

2. Diesel for Route 2 (California seaport → Dammam seaport)

= (average diesel consumed per km for deliveries from walnut farms to the California seaport using non-refrigerated trucks * traveled distance + average diesel consumed per km for shipping walnut shells from the California seaport, USA, to the Dammam seaport, KSA * Traveled distance + average diesel consumed per km for deliveries from Dammam seaport, KSA, to Aramco's facility using non-refrigerated trucks * traveled distance) * (chemical potential energy per volume).

= (8.93 km/liter * 120.7 km + 244.9 km/liter *27,924.46 km +8.93 km/liter * 27.6 km) * (5.15E+04 J/g)= 3.52E+11 J.

3. Machinery

Machinery= Σ (wight * work hours /economic life/ yearly work hours)

- Weight of a small size cargo ship is around 4.54E+10 g (50,000 tons) according to Boatinggeeks.com (2021). Working hours are estimated from Ports.com for the maritime transportation. Assuming a ship speed of 10 knots, route 1 can take about 1248 (52 days) whereas route 2 can last up to 1512 hours (63 days), thus, an average value (1380 hours) of working hours is used to estimate the emergy of machinery in the sea cargo transportation mode. For the in road transportation of walnut shells to the final destination, a light-duty nonrefrigerated truck is assume to be used and can weigh up to 2,722,008 g (Gaines et al., 2006).
- A standard container size weighs about 4000685 g (Prokeraia.com).
- Assuming an average economic life of cargo ships and equipment of 25 years (Dinu and Ilie, 2015).

Machinery used in the sea cargo transportation mode:

Small size cargo ship = 4.54E+10 g* 1380 hr = 2.51E+12 g*hr.

light-duty nonrefrigerated truck= 2.72E+06 g *8 hr= 2.18E+07 g*hr.

Standard container size = 4000685 g (Boatinggeeks.com, 2021).

Emergy of machinery= 2.51E+12 g*hr/ 25 yr/ 1380 hr/yr = 7.28E+07 g/yr.

4. Labor

According to the U.S. Bureau of labor statistics, the average annual wage for workers in cargo and freight activities in California is $49,780 for a total of 2,080 hrs/yr (Statistics, 2021).

The Emergy to money ratio for the United States in 2008 is 2.50E+12 sej/$ (NEAD, 2008).

Emergy of labor= Labor cost * Emergy/Money ratio

= 4.98E+04 \$/yr * 2.50E+12 sej/\$

= 1.25E+17 sej/yr.

5. Services for route 1
    - Cost of walnut shells: data regarding the cost of walnut shells as a raw material is estimated based on the market price listed on one of the suppliers in the United States Shipafreight.com . The cost of a 2000 pounds (907184.7g) bag is \$1199 excluding shipping costs and taxes (Shipafreight.com) .
    - Import duties and taxes: based on the available data in the Saudi Tax and Customs Authority webpage (Zakat, Tax, and Customs Authority) a 5% duty custom is applied on imports of walnut shells. Also, there is a value-added tax of 15% applied on all imports (duties will be calculated as a percentage from walnut shells cost).
    - International freight and logistics fees: shipping cost from Oakland Seaport in California, USA to Dammam Seaport in Dammam, KSA can cost between \$2000-\$8000 based on rates generated from a freight forwarder company called iContainers (https://www.icontainers.com), In general, average cost can vary depending on container dimensions, shipment weight and shipping time, thus, an average of \$5000 will be used as shipping cost.

Fuel cost is calculated with reference to the distance estimated previously. Thus:

- The cost of fuel is approximately \$0.51 per liter ("Fuel Costs in Ocean Shipping," 2018).
- A fully loaded aver size cargo ship can travel around 245 km/liters (Willow Oak Group).

- Cost of fuel used in sea cargo route 1from California seaport, USA to Jeddah seaport, KSA= $0.51 per liter*245 km/liters*22962.95 km= $2.87E+06.
- Cost of fuel used in sea cargo for route 2 from California seaport, USA to Dammam seaport, KSA= $0.51 per liter*245 km/liters*27924.46 km= $3.49E+06.
- Cargo ship costs about $1.00E+06 (Traffic, 2010).
- The Emergy to money ratio for the United States in 2008 is 2.50E+12 sej/$ (NEAD, 2008).

Total services cost for route 1= $1199+ ($1199* 5%)+($1199*15%)+
$5000+$2.87E+06+$1.00E+06 = $3.88E+06.

Emergy of services for route 1= Services Cost* Emergy/Money ratio

= $3.88E+06* 2.50E+12 sej/$

=9.70E+18 sej.

6. Services for route 2

   Total services cost for route 2= $1199+ ($1199* 5%)+($1199*15%)+
   $5000+$3.49E+06+$1.00E+06 = $4.50E+06.

Emergy of services for route 2= Services Cost* Emergy/Money ratio

= $4.50E+06* 2.50E+12 sej/$

=1.13E+19 sej.

7. Emergy of diesel for air cargo

   = (average diesel consumed per km for deliveries from walnuts farms to California seaport using non refrigerated trucks * traveled distance + average diesel consumed per km for shipping walnut shells from California seaport, USA to Jeddah seaport, KSA * traveled distance +average diesel consumed per km for deliveries from Jeddah seaport, KSA to Aramco’s facility using non-refrigerated trucks * traveled distance) * (chemical potential energy per volume).

= (8.93 km/liter * 120.7 km + 1.91 km/liter *12,846.51 km +8.93 km/liter * 49.4 km) * (5.15E+04 J/g)= 1.34E+09 J.

8. Machinery for air cargo

Machinery= Σ (wight * work hours /economic life/ yearly work hours)

- Weight of cargo aircrafts can be around 3.05E+08 g (Johnston et al., 1976). Assuming that the working hours of cargo aircrafts for international freight from Los Angeles, USA to Dammam, KSA can take about 120 hours (5 days) = 3.66E+10 g*hr (Shipafreight.com).
- Empty container weighs about 1.22E+06 g with 120 hours =1.46E+08 g*hr (Laniel et al., 2011).
- light-duty nonrefrigerated truck= 2.72E+06 g *8 hrs= 2.18E+07 g*hr.
- Assuming an average economic life of cargo ships and equipment of 27 years (Jiang, 2013).
- Working hours is estimated at 1730 hr/yr (OECD.Stat, 2021).

Emergy of air cargo machinery= 3.67E+10 g / 27 yr/ 1730 hr/yr= 7.84E+05 g/yr.

9. Labor

According to the U.S. Bureau of labor statistics, the average annual wage for workers in cargo and freight activities in California is $49,780 for a total of 2,080 hrs/yr (Statistics, 2021).

The Emergy to money ratio for the United States in 2008 is 2.50E+12 sej/$ (NEAD, 2008).

Emergy of labor= Labor cost * Emergy/Money ratio

= 4.98E+04 $/yr * 2.50E+12 sej/$

= 1.25E+17 sej/yr.

10. Services:

- Cost of walnut shells: data regarding the cost of walnut shells as a raw material is estimated based on the market price listed on one of the suppliers in the United States (http://greenhillsupply.com/product/10/walnutshells/). The cost of a 2000 pounds (907184.7g) bag is $1199 excluding shipping costs and taxes.
- Import duties and taxes: based on the available data in the Saudi Tax and Customs Authority webpage (Zakat, Tax, and Customs Authority) a 5% duty custom is applied on imports of walnut shells. Also, there is a value-added tax of 15% applied on all imports (duties will be calculated as a percentage from walnut shells cost).
- International freight and logistics fees: air cargo from California, USA to Dammam, KSA can cost between $5000- $7000 based on rates generated from UPS, air freight forwarder (https://wwwapps.ups.com/fctc/processTimeAndCost?loc=en_SA). In general, average cost can vary depending on container dimensions, shipment weight and shipping time, thus, an average of $6000 will be used as shipping cost.

Fuel cost is calculated with reference to the distance estimated previously. Thus:

- The cost of fuel is approximately $1.41 per liter (Air, 2021).
- A fully loaded cargo plane can travel around 1.91 km/liter (Willow Oak Group).
- Cost of fuel consumed by cargo plane from Los Angles Airport, USA to Dammam Airport, KSA= $1.41 per liter*1.91 km/liters*12846.51km= $3.46E+04.

- Cost of cargo plane is estimated to be \$3.00E+06 (howmuchdoescost.com, 2021).
- The Emergy to money ratio for the United States in 2008 is 2.50E+12 sej/\$ (NEAD, 2008).
- Total services cost= \$1199+ (\$1199* 5%)+(\$1199*15%)+ \$6000+\$3.46E+04 +\$3.00E+06 = \$3.04E+06.

Emergy of services= Services Cost* Emergy/Money ratio

= \$3.04E+06* 2.50E+12 sej/\$ =7.60E+18 sej.

5.4 Emergy Evaluation of Date Seed Byproducts

The following section focuses on emergy accounting calculations for the six date seed processes used by Aramco. Due to the difficulties faced in collecting data from Aramco and its licensed factory, data related to these six processes was estimated with the help of experts in the field, namely the National Center for Palms and Dates, Al-Gosaibi Company, and Al-Rafaya Company, which will be presented in more detail below. According to Amanullah et al. (2017), the amount of available date seed byproducts in Saudi Arabia is more than 150,000 tons each year; however, the exact processed volume for Aramco's use has not been disclosed by the company. As a result, in the absence of market studies and published data about date seed by-products, several assumptions must be made to arrive at a realistic estimation. Additionally, expert opinions provide a more practical view of the availability of date seed by-products in the market.

After verbal communications with several factories and experts in the date transformative market (National Center for Palms & Dates, Al-Gosaibi Company, and Al-Rafaya Company), it was concluded that the introduction of date seeds to the drilling industry by Aramco caused a substantial shortage in the amount of date seed by-product as a raw material for commercial uses.

As a result of this shortage, the price of the date seed by-products has increased significantly from around $53.33 per ton to approximately $160 per ton, according to small local businesses in the market. This huge rise in prices created a very challenging and highly competitive market for small and medium-sized date transformative factories.

According to Al-Gosaibi Company and Al-Rafaya Company, owners of date seed transformative factories, the number of seeds available on the market cannot realistically reach 150,000 tons per year, and the only reusable seeds are those generated from date paste factories. The volume of date seed is estimated based on expert opinions in the market and a feasibility study published by The National Center for Palms and Dates (2018a). Because the only reusable date seed by-products are those generated as waste from date paste factories, the number of date seeds generated is proportional to the amount of date paste produced, which is estimated to be 8 tons per day and 1280 tons per year for one factory (20 days per month and 8 months per year, given that dates are a seasonal fruit) (The National Center for Palms and Dates, 2018a). Moreover, according to the owner of Al-Gosaibi Company, approximately 9–10% of date paste production is date seeds available for commercial use. There are 90 registered factories with different types of date products, including date paste, date syrup, date vinegar, and date pastries (The General Authority for Statistics, 2020).

Statistics published by the Agricultural Development Fund (2019) show that date paste factories make up approximately 50% of date transformative factories (45 factories). Another study by Price Waterhouse Coopers (2019) states that waste generated from date paste transformative factories is estimated at 5% of the total production of date paste, which was 23,747 tons in 2012. Considering all the data previously given, an average of 57,600 tons (1280 tons/factory/year) is assumed as the annual date paste production for the 45 factories, which results in approximately 2880 tons of generated waste (5% of production). In this study, it is assumed that all the generated waste from date paste transformative factories consists of date seeds that will be used in a secondary market. Furthermore, taking into account the information given by experts in the field regarding the limited availability of date seeds as by-products, this study assumes that only 10% (288 tons) of generated waste is purchased by Aramco for use in the drilling industry.

Data about the machinery currently used in date factories and date transformative factories is estimated from previous studies. Experts in three different establishments were consulted regarding the six processes as well as adopted practices in Saudi date farms and their transformative factories. The first source was the National Center for Palms and Dates in Al-Ahsa, which is a research center that specializes in the development and advancement of date palm trees and date-related services and operations. Second, Mr. Saud Al-Gosaibi the founder of Al-Gosaibi Company has greatly contributed to the data collection process by providing detailed information about the machinery, operations, and labor required for the evaluated processes. Third, further information was provided by Al-Rafaya Company with regards to commercial uses and industrial practices of the date seeds. In addition, Aramco’s published research on the processing of date seeds into lost circulation material, as well as direct communications with the lead engineer at Saudi Aramco's Exploration and Petroleum Engineering Research Center, Dr. Amanullah, provide data on the six industrial processes (Amanullah et al., 2017; Amanullah et al., 2016). The date seed by-product remanufacturing steps comprise the following:

1- **Washing:** Tap water is used to clean the seeds, and a mechanized manual strainer is used to ensure that the seeds are free of any residues. Seeds may be washed with a high-pressure water jet to remove dirt. Another source indicates that the date seeds are washed with fresh water. The purchased date seed volume is estimated based on historical data and previous studies at 3.845E+09 g at a price of $160 per ton.

2- **Drying:** The seeds are then dried in an oven at 80 °C (175 °F) for 2 hours to remove any moisture, which enhances the grinding process. Seeds can also be sun-dried for a period of time under atmospheric conditions.

3- **Roasting:** Date seeds are roasted using thermal treatment to remove any excess moisture. Seeds are placed in a dry environment for 2–3 days under ambient laboratory conditions.

4- **Grinding:** After cooling, the seeds are ground by placing them in the sample placement chamber of a programmable grinding machine. This step generates a loss in the volume of processed seeds (called the "loss on grinding index") of up to 8%, according to experimental laboratory results conducted by Amanullah et al. (2016).

5- **Sieving:** To separate particles of varying sizes, a sieving machine is used.

6- **Storing:** The processed particles are stored to await delivery to Aramco's facility.

In Sections 5.4.1, 5.4.2, 5.4.3, 5.4.4, and 5.4.5, an in-depth examination of the six industrial processes is given using EA. Each process is evaluated, taking into account all the inputs to each process separately. Table 5-5 presents an exemplary list of machinery used in the six industrial processes run using purchased resources brought from sources outside the system's boundaries.

Table 5-5: Examples of Date and Pits Industrial Machinery

Machine name	Machine weight	Source
Pitting machine	-Weight: 400 Kg. (4.00E+05 g) -Power 2.2 kw - Capacity: 150 kg/hr - Price: $3000	Alibaba.com
Washing machine	-Dimensions of washing tank: L 200cm, W100cm, h 80cm. Washing conveyor -Material: stainless steel -Water pump: 0.75 kWh, 38 -Power: 1.5 kWh -Production capacity: 500 kg/hr -Water volume: 100L/hr -Weight approximately :500k -Price in average $3000	Mzadtamr.com Alibaba.com
Thermal drying oven	-Weight: 150 kg -Material: stainless steel -Power: 15 kWh -Price: 3680 $	Alibaba.com
Industrial Grinding machines	-Stainless steel -Weight 280 kg -C–pacity: 30 - 100 kg/hr -Power: 5.5 KW Price: $2869	Alibaba.com
Sieving machine	-Weight: 220 kg -Material: Stainless Steel and carbon steel -Power: 0.75 kw -Price: $2900 average cost	Alibaba.com
Packing machine	-Weight: 140 kg -Material: stainless steel -Capacity: 8-10 bag/minute. -Power= 0.76 kWh -Price: 1280 $	Alibaba.com

5.4.1 Emergy Evaluation of Process Step 1, Washing Date Seeds

Process 1 is evaluated using EA, which comprises all inputs to the process of washing the date seed by-products. Table 5-6 outlines all inputs (items) to this process, with detailed emergy calculations presented below. The first column, “item,” represents the resources included in the evaluation. The second column, “raw amount,” is the available energy within each resource. The third column shows the unit used for each resource. The fourth column is the UEV for each resource, which represents all the previous environmental activities that have taken place to produce each resource. UEVs are used from previous studies, which are referenced in the fifth column. Finally, the sixth column presents the emergy value of each resource flowing into the system after conversion.

Table 5-6: Emergy Evaluation of Process 1, Washing Date Seeds

Item	Raw Amount	Unit	UEV (sej/unit)	Reference	Emergy flows (sej/yr)
Purchased (imported) resources (IM)					
1. Transported date seeds	3.88E+08	g	6.49E+07[1]	This study	2.51E+16
2. Tap water	4.94E+05	J	4.10E+04	(Arding and Brown, 1991)	2.03E +10
3. Machinery	9.00E+05	g	6.70E+09	(Arding and Brown, 1991)	6.03E+15
4. Electricity	1.40E+11	J/yr	1.60E+05	(Odum, 1996)	2.24E+16
5. Labor	2.15E+04	sej/yr	--	(NEAD, 2008)	1.31E +17
6. Services	1.01E+05	$/yr	--	This study	6.18E+17
Total Emergy (with L&S)					8.03E+17
Total Emergy (without L&S)					5.35E+16
Washed date seeds mass	3.88E+08	g	--	Estimated	--
Energy content*	4.78E+12	J	--	This study	--
Specific emergy (with L&S)[2]	--	sej/g	2.01E+09	This study	--
Specific emergy (without L&S)[3]	--	sej/g	1.16E+08	This study	--
UEV with L&S[4]	--	sej/j	1.63E+05	This study	--
UEV without L&S[5]	--	sej/J	9.40E+03	This study	--

Units are defined in the appendix, Table 10-1.
*Energy content per gram of date seeds is 1.23E+04 J (Kamel et al., 1981). For the mass of date seeds processed, the energy content is 3.88E+08 *1.23E+04 =4.78E+12.
[1] UEV of date seeds= transported date seeds specific emergy (without L&S) 6.49E+07 sej/g.
[2] Specific emergy (with L&S) = Total emergy (with L&S) 8.03E+17/ transported date seed 3.88E+08.
[3] Specific emergy (without L&S) = Total emergy (without L&S) 5.35E+16/ transported date seeds 3.88E+08.
[4] UEV with L&S of washed date seeds= Total emergy (with L&S) 8.03E+17/ Energy conten4.78E+12.
[5] UEV without L&S of washed date seeds = Total emergy (without L&S) 5.35E+16/ Energy content 4.78E+12.

1. Emergy of transported date seeds= Volume of transported date seeds* UEV of transported date seeds

Volume of transported date seeds is estimated at 3.88E+08 g (The National Center for Palms and Dates, 2018a).

UEV of transported date seeds is calculated in Section 5.3.1, Table 5-3.

2. Fresh water= Volume of fresh water= 0.1 m^3/h (based on the washing machine manufacturer), Gibbs free energy of water=4.94 J/g (Odum, 1996), water density=1.00E+06 g/ m^3.

Energy in fresh water= 0.1 m^3/h *4.94 J/g*1.00E+06 g/ m^3=4.94E +05 J.

3. Machinery= Σ (Steel weight, g* Machinery UEV)

In a previous process, a pitting machine was used to extract seeds and then sell them as by-products.

Steel weight in pitting machine= 4.00E+05 g .

Steel weight in washing machine= 5.00E+05 g.

Total weight of machinery =9.00E+05 g.

4. Electricity= total consumption* energy per kWh

Total consumption= (pitting machine, 2.2 kWh*8766 hr/yr) + (washing machine, 0.75kWh*8766 hr/yr + 1.5 kWh*8766 hr/yr) = 1.93E+04 kWh/yr +1.97E+04 kWh/yr= 3.90E+04 kWh/yr.

Energy per kWh= 3.60E+06 J/kWh (Jiang et al., 2007).

Electricity= 3.90E+04 kWh/yr* 3.60E+06 J/kWh = 1.40E+11 J/yr.

5. Labor

Average labor cost per year for in dates transformative factories is 21,472 $ per year, assuming a number of 30 workers in an average size factory (The National Center for Palms and Dates, 2018a)

Emergy of labor= Labor cost * Emergy/Money ratio for Saudi Arabia in 2008 (NEAD, 2008).

= (2.15E+04 $/yr)*(6.10E+12 sej/$)= 1.31E +17 sej/yr.

6. Services

Emergy of services= Services Cost * Emergy/Money ratio

Services cost:

Machinery cost= $6.00E+03.

For electricity, based on the Saudi Electricity Company tariffs for agricultural consumption (SEC) the cost per kWh is $0.042 for if consumption is less that 6000 kWh, and $0.053 for more than that. Cost of electricity consumption for agricultural activities is subsidized. Thus, the cost of electricity for the investigated system is:

Electricity cost (6000 kWh*$0.042/kWh + 33000 kWh * $0.053/Kwh) = $2.00E+03.

Other one-time expenses include:

Average land cost for date transformative factories is around $63.96/yr (The National Center for Palms and Dates, 2018a).

Cost of infrastructure $9.33E+04.

Total services cost= machinery cost + electricity cost + other one-time expenses

=\$6.00E+03 + \$2.00E+03 + \$63.96/yr + \$9.33E+04= \$1.01E+05/yr.

Emergy of services= services cost* Emergy/Money ratio for Saudi Arabia in 2008 (NEAD, 2008).

= \$1.01E+05 /yr* 6.10E+12 sej/\$ = 6.18E+17 sej/yr.

5.4.2 Emergy Evaluation of Process 2 and 3, Drying and Roasting Date Seeds

Processes 2 and 3 are evaluated using EA. All inputs to the processes of drying and roasting the washed date seed by-products are included in the evaluation. Table 5-7 outlines the major inputs to these two processes, with detailed emergy calculations, assumptions and references presented below.

Table 5-7: Emergy Evaluation of Process 2 and 3, Drying and Roasting Date Seeds

Item	Raw Amount	Unit	UEV (sej/unit)	Reference	Emergy flows (sej/yr)
Purchased (imported) resources (IM)					
1. Washed date seeds	3.88E+08	g	1.16E+08[1]	This study	4.50E+16
2. Machinery	1.50E+05	g	4.10E+04	(Arding and Brown, 1991)	6.15E+09
3. Electricity	4.73E+11	J/yr	1.60E+05	(Odum, 1996)	7.57E+16
4. Labor	2.15E+04	\$/yr	--	This study	1.31E +17
5. Services	1.06E+04	\$/yr	--	This study	6.44E+16
Total Emergy (with L&S)					3.00E+17
Total Emergy (without L&S)					1.01E+17
Dried and roasted date seeds mass	3.88E+08	g	--	Estimated	--
Energy content*	7.10E+12	J	--	This study	--
Specific emergy (with L&S)[2]	--	sej/g	7.81E+08	This study	--

Specific emergy (without L&S)[3]	--	sej/g	2.76E+08	This study	--
UEV with L&S[4]	--	sej/j	4.27E+04	This study	--
UEV without L&S[5]	--	sej/J	1.51E+04	This study	--

Units are defined in the appendix, Table 10-1.

*Energy content per gram of roasted date seeds is 1.83E+04 J (Rahman et al., 2007). For the mass of dates produced,the energy content is 3.88E+08*1.83E+04 =7.10E+12.

[1] UEV of date seeds= washed date seeds specific emergy (without L&S) 8.12 sej/g.

[2] Specific emergy (with L&S) = Total emergy (with L&S) 9.15E+17/ Dried and roasted date seed 3.88E+08.

[3] Specific emergy (without L&S) = Total emergy (without L&S) 7.20E+17/ transported date seeds 3.88E+08.

[4] UEV with L&S of washed date seeds= Dates specific emergy (with L&S) 9.15E+17/ Energy content 7.10E+12.

[5] UEV without L&S of washed date seeds = Total emergy (with L&S) 7.20E+17/ Energy content 7.10E+12.

1. Emergy of washed date seeds:

The emergy of the washed date seeds= amount of date seeds washed in grams× washed date seeds UEV

=3.88E+08g/yr ×8.12E+07 sej/g = 3.15E+16 sej/yr.

2. Machinery= Σ (Steel weight, g* Machinery UEV).

Processes 2 and 3 are combined as they both use the same machine which is thermal drying oven to dry and roast the date seeds after the washing process.

Steel weight in thermal drying machine= 1.50E+05 g.

3. Electricity= total consumption* energy per kWh

Total consumption= (thermal drying oven, 15 kWh*8766 hr/yr) = 1.31E+05 kWh/yr.

Energy per kWh= 3.60E+06 J/kWh (Jiang et al., 2007).

Electricity= 1.31E+05 kWh/yr* 3.60E+06 J/kWh = 4.73E+11J/yr.

4. Labor

Average labor cost per year for in dates transformative factories is 21,472 $ per year, assuming a number of 30 workers in an average size factory (The National Center for Palms and Dates, 2018a).

Emergy of labor= Labor cost * Emergy/Money ratio for Saudi Arabia in 2008

= (2.15E+04 $/yr)*(6.10E+12 sej/$)= 1.31E +17 sej/yr.

5. Services

Emergy of services= Services Cost * Emergy/Money ratio

Services Cost:

Machinery cost= $3.68E+03.

For electricity, based on the Saudi Electricity Company (SEC) tariffs for agricultural consumption the cost per kWh is $0.042 for if consumption is less that 6000 kWh, and $0.053 for more than that. Cost of electricity consumption for agricultural activities is subsidized. Thus, the cost of electricity for the investigated system is:

Electricity cost (6000 kWh*$0.042/ kWh + 125000 kWh * $0.053/ kWh) = $ 6.88E+03.

Total services cost= machinery cost + electricity cost

=$3.68E+03+ $6.88E+03 = $1.06E+04.

Emergy of services= services cost* Emergy/Money ratio for Saudi Arabia in 2008 (NEAD, 2008)

= $1.06E+04* 6.10E+12 sej/$ = 6.44E+16 sej.

5.4.3 Emergy Evaluation of Process 4, Grinding Date Seeds

Process 4 is evaluated using EA, which comprises all inputs to the processes of grinding the dried and roasted date seed by-products by using a programmable grinding machine. Table 5-8 outlines all inputs to this process, with detailed emergy calculations presented below.

Table 5-8: Emergy Evaluation of Process 4, Grinding Date Seeds

(About 8% of the grinded seeds are lost during the grinding process)

Item	Raw Amount	Unit	UEV (sej/unit)	Reference	Emergy flows (sej/yr)
Purchased (imported) resources (IM)					
1. Dried and roasted date seeds	3.88E+08	g	2.76E+08[2]	This study	1.07E+17
2. Machinery	8.30E+01	g	4.10E+04	(Arding and Brown, 1991)	3.40E+06
3. Electricity	1.74E11	J/yr	1.60E+05	(Odum, 1996)	2.78E+16
4. Labor	2.15E+04	$/yr	--	This study	1.31E +17
5. Services	4.98E+03	$/yr	--	This study	3.04E+16
Total Emergy (with L&S)					2.96E+17
Total Emergy (without L&S)					1.35E+17
Ground date seeds mass[1]	3.57E+08	g	--	Estimated	--
Energy content*	7.18E+12	J	--	This study	--
Specific emergy (with L&S)[3]	--	sej/g	8.29E+08	This study	--
Specific emergy (without L&S)[4]	--	sej/g	3.78E+08	This study	--
UEV with L&S[5]	--	sej/j	4.12E+04	This study	--
UEV without L&S[6]	--	sej/J	1.89E+04	This study	--

Units are defined in the appendix, Table 10-1.
*Energy content per gram of ground date seeds is 2.01E+04 J/g (Juhaimi et al., 2012) . For the mass of roasted and dried dates seeds, the energy content is 3.57E+08*1.83E+04 =7.18E+12.
[1] Ground date seeds mass= volume of date seeds 3.88E+08- 3.88E+08* 0.08.
[2] UEV of date seeds= dried and roasted date seeds specific emergy (without L&S) 2.768 sej/g.
[3] Specific emergy (with L&S) = Total emergy (with L&S) 9.11E+17/ ground date seeds 3.57E+08.
[4] Specific emergy (without L&S) = Total emergy (without L&S) 7.49E+17/ ground date seed3.57E+08.
[5] UEV with L&S = Dates specific emergy (with L&S) 9.11E+17/ Energy conten7.18E+12.
[6] UEV without L&S = Total emergy (with L&S) 7.49E+17/ Energy content 7.18E+12.

In process 4, the dry roasted seeds are ground into powder using an industrial grinder. In this process %8 of the ground seeds are lost during the process (Amanullah et al., 2017). Thus, the volume of the date seeds is reduced in process 5.

1. Emergy of machinery= Σ (steel × work hours /economic life/yearly work hours).

Industrial grinding machine= (Steel weight, 2.80E+05 g × work hours, 4 h) =1.12E+06, (Working hours are estimated and they may vary depending on the volume of processed seeds). Assuming an average economic life of 25 years based on (Rates, 2020) . yearly working hours are estimated at 540 and may vary depending on the availability of the processed date seeds.

Emergy of machinery = 1.12E+06 g*h /25 yr /540 hr/yr= 8.30E+01 g/ yr.

2. Electricity= total consumption* energy per kWh

Total consumption= (Industrial grinder, 5.5 kWh*8766 h/yr) = 4.82E+04 kWh/yr.

Energy per kWh= 3.60E+06 J/kWh (Jiang et al., 2007).

Electricity= 4.82E+04 kWh/yr* 3.60E+06 J/kWh = 1.74E+11 J/yr.

3. Services

Emergy of services= Services Cost * Emergy/Money ratio

Services Cost:

4. Machinery cost= $2.87E+03.

For electricity, based on the Saudi Electricity Company (SEC) tariffs for agricultural consumption the cost per kWh is $0.042 for if consumption is less that 6000 kWh, and $0.053 for more than that. Cost of electricity consumption for agricultural activities is subsidized. Thus, the cost of electricity for the investigated system is:

5. Electricity cost (6000 kWh*$0.042 + 42,200 kWh * $0.053) = $2.49E+03.

Total services cost= machinery cost + electricity cost

=$2.87E+03 + $2.49E+03 = $4.98E+03.

Emergy of services= services cost* Emergy/Money ratio for Saudi Arabia in 2008 (NEAD, 2008)

= $4.98E+03* 6.10E+12 sej/$ = 3.04E+16 sej.

5.4.4 Emergy Evaluation of Process 5, Sieving Date Seeds

Process 5 is evaluated using EA, which comprises all inputs to the process of sieving the ground date seed by-products, using a sieving machine. Table 5-9 outlines all inputs to this process, with detailed emergy calculations presented below.

Table 5-9: Emergy Evaluation of Process 5, Sieving Date Seeds

Item	Raw Amount	Unit	UEV (sej/unit)	Reference	Emergy flows (sej/yr)
Purchased (imported) resources (IM)					
1. Ground date seeds	3.57E+08	g	3.78E+08[2]	This study	1.35E+17
2. Machinery	4.01E+02	g	4.10E+04	(Arding and Brown, 1991)	1.65E+07
3. Electricity	2.37E+10	J/yr	1.60E+05	(Odum, 1996)	3.79E+15
4. Labor	2.15E+04	$/yr	--	This study	1.31E+17
5. Services	3.18E+03	$/yr	--	This study	1.94E+16
Total Emergy (with L&S)					2.90E+17
Total Emergy (without L&S)					1.39E+17
Sieved date seeds mass[1]	1.79E+08	g	--	Estimated	--
Energy content*	3.60E+12	J	--	This study	--
Specific emergy (with L&S)	--	sej/g	1.62E+09	This study	--
Specific emergy (without L&S)	--	sej/g	7.77E+08	This study	--
UEV with L&S[1]	--	sej/j	8.06E+04	This study	--
UEV without L&S[2]	--	sej/J	3.86E+04	This study	--

Units are defined in the appendix, Table 10-1.

*Energy content per gram of ground date seeds is 2.01E+04 J/g (Juhaimi et al., 2012) . For the mass of sieved dates seeds, the energy content is 1.79E+08*2.01E+04 =3.60E+12.

[1] Assuming that only 50% of the sieved date seeds match the size requirements as lost circulation materials and the rest are lost during the sieving process (3.57E+08- 3.5708*0.50).

[2] UEV of date seeds= ground date seeds specific emergy (without L&S) 3.78E+08 sej/g.

[3] Specific emergy (with L&S) = Total emergy (with L&S) 2.90E+17/ sieved date seeds 1.79E+08.

[4] Specific emergy (without L&S) = Total emergy (without L&S) 1.39E+17/ sieved date seed1.79E+08.

[5] UEV with L&S = Dates specific emergy (with L&S) 2.90E+17/ Energy conten3.60E+12.

[6] UEV without L&S = Total emergy (with L&S) 1.39E+17/ Energy content 3.60E+12.

1. Emergy of machinery= Σ (steel × work hours /economic life/yearly work hours).

Sieving machine = (Steel weight, 6.50E+05 g × work hours, 4 h) =2.60E+06, (Working hours are estimated and they may vary depending on volume on processed seeds).

Assuming an average economic life of 12 years based on ("ATO Depreciation Rates- Sieve," 2020) . yearly working hours are estimated at 540 and may vary depending on the availability of the processed date seeds.

Emergy of machinery = 2.60E+06/12/540 = 4.01E+02 g/ h.

2. Electricity= Total consumption* Energy per kWh

Total consumption= (Sieving machine, 0.75 kWh*8766 hr/yr) = 6.57E+03 kWh/yr.

Energy per kWh= 3.60E+06 J (Jiang et al., 2007).

Electricity= 6.57E+03 kWh/yr * 3.60E+06 J

= 2.37E+10 J/yr.

3. Emergy of services= Services Cost * Emergy/Money ratio

Services Cost:

4. Machinery cost= $2.90E+03.

For electricity, based on the Saudi Electricity Company tariffs for agricultural consumption the cost per kWh is $0.042 for if consumption is less that 6000 kWh, and $0.053 for more than that. Cost of electricity consumption for agricultural activities is subsidized. Thus, the cost of electricity for the investigated system is:

5. Electricity cost (6000 kWh*$0.042/ kWh+ 574.5 kWh * $0.053/ kWh) = $2.82E+02.

Total services cost= machinery cost + electricity cost

=$2.90E+03 + $2.82E+02 = $3.18E+03.

Emergy of services= services cost* Emergy/Money ratio for Saudi Arabia in 2008 (NEAD, 2008) = $4.98E+03* 6.10E+12 sej/$ = 1.94E+16 sej.

5.4.5 Emergy Evaluation of Process 6, Storing Date Seeds

Process 6 is evaluated using EA, which comprises all inputs to the process of storing the processed date seed by-products. Table 5-10 outlines all inputs to this process, with detailed emergy calculations presented below.

Table 5-10: Emergy Evaluation of Process 6, Storing Date Seeds

Item	Raw Amount	Unit	UEV (sej/unit)	Reference	Emergy flows (sej/yr)
Purchased (imported) resources (IM)					
1. Sieved date seeds mass	1.79E+08	g	7.77E+08[1]	This study	1.39E+17
2. Machinery	1.03E+02	g	4.10E+04	(Arding and Brown, 1991)	1.22E+07
3. Electricity	2.40E+10	J/yr	1.60E+05	(Odum, 1996)	3.84E+15
4. Labor	2.15E+04	$/yr	--	This study	1.31E +17
5. Services	1.57E+03	$/yr	--	This study	9.56E+15
Total Emergy (with L&S)					2.83E+17
Total Emergy (without L&S)					1.43E+17
Stored processed date seeds mass	1.79E+08	g	--	Estimated	--
Energy content*	3.60E+12	J	--	This study	--
Specific emergy (with L&S)[2]	--	sej/g	4.97E+09	This study	--
Specific emergy (without L&S)[3]	--	sej/g	7.99E+08	This study	--
UEV with L&S[4]	--	sej/j	7.86E+04	This study	--
UEV without L&S[5]	--	sej/J	3.97E+04	This study	--

Units are defined in the appendix, Table 10-1.

*Energy content per gram of ground date seeds is 2.01E+04 J/g (Juhaimi et al., 2012) . For the mass of stored dates seeds, the energy content is 1.79E+08*2.01E+04 =3.60E+12.

[1] UEV of date seeds= sieved date seeds specific emergy (without L&S) 7.78sej/g.

[2] Specific emergy (with L&S) = Total emergy (with L&S) 8.89E+17/ stored date seed79E+08.

[3] Specific emergy (without L&S) = Total emergy (without L&S) 7.49E+17/ stored date seeds 1.79E+08.

[4] UEV with L&S = Total emergy (with L&S) 8.89E+17/ Energy conten3.60E+12.

[5] UEV without L&S = Total emergy (with L&S) 7.49E+17/ Energy content 3.60E+12.

In this last process, the sieved particles are packed awaiting transfer to the final location.

1. Emergy of machinery= Σ (steel × work hours /economic life/yearly work hours).

Packing machine= (Steel weight, 1.40E+05 g × work hours, 4 h) =5.60E+05, (Working hours are estimated based on a comparative study by (Al-Hameedi et al., 2020).

Assuming an average economic life of 10 years ("ATO Depreciation Rates- Packing," 2020), 540 working hours depending on the availability of the processed date seeds.

Emergy of machinery = 5.60E+05/10/540=1.03E+02 g/ h.

2. Electricity= total consumption* energy per kWh

Total consumption= (Packing machine, 0.76 kWh*8766 hr/yr) = 6.67E+03 kWh/yr.

Energy per kWh= 3.60E+06 J/kWh (Jiang et al., 2007).

Electricity= 6.67E+03 kWh/yr* 3.60E+06 J/kWh = 2.40E+10 J/yr.

3. Emergy of services= Services Cost * Emergy/Money ratio

Services Cost:

4. Machinery cost= $1.28E+03.

For electricity, based on the Saudi Electricity Company (SEC) tariffs for agricultural consumption the cost per kWh is $0.042 for if consumption is less that 6000 kWh, and $0.053 for more than that. Cost of electricity consumption for agricultural activities is subsidized. Thus, the cost of electricity for the investigated system is:

5. Electricity cost (6000 kWh*$0.042/ kWh + 662.16 kWh * $0.053/ kWh) = $2.87E+02.

Total services cost= machinery cost + electricity cost

=$1.28E+03 + $2.87E+02 = $1.57E+03.

Emergy of services= services cost* Emergy/Money ratio for Saudi Arabia in 2008(NEAD, 2008)

= $1.57E+03 * 6.10E+12 sej/$ = 9.56E+15 sej.

5.5 Emergy Evaluation of Walnut Shell Byproducts

Due to limitations in available data regarding the transformation processes of walnut shells into lost circulation materials, it is assumed that walnut shell processing follows the same industrial processes performed on the date seed by-products (Amanullah et al., 2017; Amanullah et al., 2016), which are done locally. Thus, the same calculations performed in Section 5.4 for the conversion of all date seed inputs to the six processes are duplicated for the walnut shells as well. Tables 5-11 through 5-15 illustrate the emergy evaluation of all the industrial processes of transforming walnut shell by-products into lost circulation material.

5.5.1 Emergy Evaluation of Process 1, Washing Walnut Shells

Table 5-11: Emergy Evaluation of Process 1, Washing Walnut Shells

Item	Raw Amount	Unit	UEV (sej/unit)	Reference	Emergy flows (sej/yr)
Purchased (imported) resources (IM)					
1. Transported date seeds	3.88E+08	g	3.87E+08[1]	This study	1.50E+17
2. Tap water	4.94E+05	J	4.10E+04	(Arding and Brown, 1991)	2.03E +10
3. Machinery	9.00E+05	g	6.70E+09	(Arding and Brown, 1991)	6.03E+15
4. Electricity	1.40E+11	J/yr	1.60E+05	(Odum, 1996)	2.24E+16
5. Labor	2.15E+04	$/yr	--	(NEAD, 2008)	1.31E +17
6. Services	1.01E+05	$/yr	--	This study	6.18E+17
Total Emergy (with L&S)					9.30E+17
Total Emergy (without L&S)					1.78E+17
Washed date seeds mass	3.88E+08	g	--	Estimated	--
Energy content*	7.45E+12	J	--	This study	--
Specific emergy (with L&S)[2]	--	sej/g	2.43E+09	This study	--
Specific emergy (without L&S)[3]	--	sej/g	4.59E+08	This study	--
UEV with L&S[4]	--	sej/j	1.27E+05	This study	--
UEV without L&S[5]	--	sej/J	2.39E+04	This study	--

Units are defined in the appendix, Table 10-1.
*Energy content per gram of walnut shells is 1.92E+04 J (Onay et al., 2004).For the mass of washed walnut shells, the energy content is 3.88E+08*1.92E+04 =7.45E+12.

[1] UEV of walnut shells= air transported walnut shells specific emergy (without L&S) 3.87E+08 sej/g.

[2] Specific emergy (with L&S) = Total emergy (with L&S) 9.44E+17/ transported walnut shell88E+08.

[3] Specific emergy (without L&S) = Total emergy (without L&S) 1.95E+17/ transported walnut shells 3.88E+08.

[4] UEV with L&S of washed walnut shells= Total emergy (with L&S) 9.44E+17/ Energy conten7.45E+12.

[5] UEV without L&S of washed walnut shells = Total emergy (without L&S) 1.95E+17/ Energy content 12.

5.5.2 Emergy Evaluation of Process 2 and 3, Drying and Roasting Walnut Shells

Table 5-12: Emergy Evaluation of Process 2 and 3, Drying and Roasting Walnut Shells

Item	Raw Amount	Unit	UEV (sej/unit)	Reference	Emergy flows (sej/yr)
Purchased (imported) resources (IM)					
1. Washed walnut shells	3.88E+08	g	4.59E+08[1]	This study	1.80E+17
2. Machinery	1.50E+05	g	4.10E+04	(Arding and Brown, 1991)	6.15E+09
3. Electricity	4.73E+11	J/yr	1.60E+05	(Odum, 1996)	7.57E+16
4. Labor	2.15E+04	$/yr	--	This study	1.31E +17
5. Services	1.06E+04	$/yr	--	This study	6.44E+16
Total Emergy (with L&S)					4.51E+17
Total Emergy (without L&S)					2.60E+17
Dried and roasted date seeds mass	3.88E+08	g	--	Estimated	--
Energy content*	7.45E+12	J	--	This study	--
Specific emergy (with L&S)[2]	--	sej/g	1.20E+09	This study	--
Specific emergy (without L&S)[3]	--	sej/g	6.98E+08	This study	--
UEV with L&S[4]	--	sej/j	6.26E+04	This study	--
UEV without L&S[5]	--	sej/J	3.64E+04	This study	--

Units are defined in the appendix, Table 10-1.
*Energy content per gram of walnut shells is 1.92E+04 J (Onay et al., 2004).For the mass of washed walnut shells, the energy content is 3.88E+08*1.92E+04 =7.45E+12.

[1] UEV of date seeds= washed walnut shells specific emergy (without L&S) 5.03 sej/g.

[2] Specific emergy (with L&S) = Total emergy (with L&S)4.66E+17/ Dried and roasted walnut shell88E+08.

[3] Specific emergy (without L&S) = Total emergy (without L&S) 2.71E+17/ Dried and roasted walnut shells 3.88E+08.

[4] UEV with L&S = Dates specific emergy (with L&S) 4.66E+17/ Energy conten7.45E+12.

[5] UEV without L&S = Total emergy (with L&S) 2.71E+17/ Energy content+12.

5.5.3 Emergy Evaluation of Process 4, Grinding Walnut Shells

Table 5-13: Emergy Evaluation of Process 4, Grinding Walnut Shells

Item	Raw Amount	Unit	UEV (sej/unit)	Reference	Emergy flows (sej/yr)
Purchased (imported) resources (IM)					
1. Dried and roasted date seeds	3.88E+08	g	6.98E+08[2]	This study	2.71E+17
2. Machinery	8.30E+01	g	4.10E+04	(Arding and Brown, 1991)	3.40E+06
3. Electricity	1.74E11	J/yr	1.60E+05	(Odum, 1996)	2.78E+16
4. Labor	2.15E+04	$/yr	--	This study	1.31E +17
5. Services	4.98E+03	$/yr	--	This study	3.04E+16
Total Emergy (with L&S)					4.60E+17
Total Emergy (without L&S)					2.99E+17
Ground walnut shells mass[1]	3.57E+08	g	--	Estimated	--
Energy content*	6.85E+12	J	--	This study	--
Specific emergy (with L&S)[3]	--	sej/g	1.29E+09	This study	--
Specific emergy (without L&S)[4]	--	sej/g	8.38E+08	This study	--
UEV with L&S[5]	--	sej/j	6.72E+04	This study	--
UEV without L&S[6]	--	sej/J	4.36E+04	This study	--

Units are defined in the appendix, Table 10-1.

*Energy content per gram of ground walnut shells is assumed to be 1.92E+04 J (Onay et al., 2004).For the mass of dried and roasted walnut shells, the energy content is 3.57E+08*1.92E+04 =6.85E+12.

[1] Ground walnut shells mass= volume of walnut shells 3.88E+08- 3.8808* 0.08.

[2] UEV of walnut shells= dried and roasted date seeds specific emergy (without L&S) 6.988 sej/g.

[3] Specific emergy (with L&S) = Total emergy (with L&S) 5.59E+17/ ground date seeds 3.57E+08.

[4] Specific emergy (without L&S) = Total emergy (without L&S) 3.98E+17/ ground date seed3.57E+08.

[5] UEV with L&S = Dates specific emergy (with L&S) 5.59E+17 / Energy conten6.85E+12.

[6] UEV without L&S = Total emergy (with L&S) 3.98E+17/ Energy content 12.

5.5.4 Emergy Evaluation of Process 5, Sieving Walnut Shells

Table 5-14: Emergy Evaluation of Process 5, Sieving Walnut Shells

Item	Raw Amount	Unit	UEV (sej/unit)	Reference	Emergy flows (sej/yr)
Purchased (imported) resources (IM)					
1. Ground walnut shells	3.57E+08	g	8.38E+08[2]	This study	2.99E+17
2. Machinery	4.01E+02	g	4.10E+04	(Arding and Brown, 1991)	1.65E+07
3. Electricity	2.37E+10	J/yr	1.60E+05	(Odum, 1996)	3.79E+15
4. Labor	2.15E+04	$/yr	--	This study	1.31E+17
5. Services	3.18E+03	$/yr	--	This study	1.94E+16
Total Emergy (with L&S)					4.53E+17
Total Emergy (without L&S)					3.03E+17
Sieved walnut shells mass[1]	1.79E+08	g	--	Estimated	--
Energy content*	3.44E+12	J	--	This study	--
Specific emergy (with L&S)[3]	--	sej/g	2.53E+09	This study	--
Specific emergy (without L&S)[4]	--	sej/g	1.70E+09	This study	--
UEV with L&S[5]	--	sej/j	1.32E+05	This study	--
UEV without L&S[6]	--	sej/J	8.81E+04	This study	--

Units are defined in the appendix, Table 10-1.

* Energy content per gram of ground walnut shells is assumed to be 1.92E+04 J (Onay et al., 2004).For the mass of sieved walnut shells, the energy content is 1.79E+08*1.92E+04 =3.44E+12.

[1] Assuming that only 50% of the sieved walnut shells match the size requirements as lost circulation materials and the rest are lost during the sieving process (3.57E+08- 3.5708*0.50).

[2] UEV of walnut shells= ground walnut shells specific emergy (without L&S) 8.388 sej/g.

[3] Specific emergy (with L&S) = Total emergy (with L&S) 5.59E+17/ sieved walnut shells 1.79E+08.

[4] Specific emergy (without L&S) = Total emergy (without L&S) 3.98E+17/ sieved walnut shell1.79E+08.

[5] UEV with L&S of = walnut shells specific emergy (with L&S) 5.59E+17 / Energy content 3.44E+12.

[6] UEV without L&S = Total emergy (with L&S) 3.98E+17/ Energy content E+12.

5.5.5 Emergy Evaluation of Process 6, Storing Walnut Shells

Table 5-15: Emergy Evaluation of Process 6, Storing Walnut Shells

Item	Raw Amount	Unit	UEV (sej/unit)	Reference	Emergy flows (sej/yr)
Purchased (imported) resources (IM)					
1. Sieved date seeds mass	1.79E+08	g	1.70E+09[1]	This study	3.03E+17
2. Machinery	1.03E+02	g	4.10E+04	(Arding and Brown, 1991)	1.65 E+07
3. Electricity	2.40E+10	J/yr	1.60E+05	(Odum, 1996)	3.84E+15
4. Labor	2.15E+04	$/yr	--	This study	1.31E +17
5. Services	1.57E+03	$/yr	--	This study	9.56E+15
Total Emergy (with L&S)					4.48E+17
Total Emergy (without L&S)					3.07E+17
Stored processed date seeds mass	1.79E+08	g	--	Estimated	--
Energy content*	3.44E+12	J	--	This study	--
Specific emergy (with L&S)[2]	--	sej/g	2.50E+09	This study	--
Specific emergy (without L&S)[3]	--	sej/g	1.72E+09	This study	--
UEV with L&S[4]	--	sej/j	1.30E+05	This study	--
UEV without L&S[5]	--	sej/J	8.92 E+04	This study	--

Units are defined in the appendix, Table 10-1.

* Energy content per gram of ground walnut shells is assumed to be 1.92E+04 J (Onay et al., 2004).For the mass of stored walnut shells, the energy content is 1.79E+08*1.92E+04 =3.44E+12.

[1] UEV of walnut shells= sieved walnut shells specific emergy (without L&S) 2.209sej/g.

[2] Specific emergy (with L&S) = Total emergy (with L&S) 5.44E+17/ stored walnut shell.79E+08.

[3] Specific emergy (without L&S) = Total emergy (without L&S) 4.04E+17/ stored walnut shells 1.79E+08.

[4] UEV with L&S = Total emergy (with L&S) 5.44E+17/ Energy content 3.44E+12.

[5] UEV without L&S = Total emergy (with L&S) 4.04E+17/ Energy content 3.44E+12.

This chapter has covered extensive emergy evaluations of date cultivation (Section 5.1), walnut cultivation (Section 5.2), date seed transportation (Section 5.3.1), walnut shell transportation (Section 5.3.2), date seed by-product processing (Section 5.4), and walnut shell by-product processing (Section 5.5). Initial analysis of the date seed by-product supply chain and the walnut shell by-product supply chain results suggests that not all of the supply chain tiers are performing sustainably. When comparing the two crops—dates, and walnuts—it is clear that walnuts are more efficient in terms of resource utilization during production (renewable and non-renewable). Results show that walnut cultivation uses more emergy from renewable resources during production (3.81E+19 sej/yr) and less emergy of non-renewable resources (1.95E+20 sej/yr) (Section 5.2, Table 5-2). Contrarily, date production uses less emergy from renewable resources (2.18E+19 sej/yr) and is highly dependent on the emergy of non-renewable resources (2.27E+20 sej/yr) (Section 5.1, Table 5-1). Table 5-16 provides an aggregate view of the evaluated supply chains by presenting the emergy indicators for both supply chains.

Table 5-16: Emergy-Based Indicators Calculations

Emergy Indicators	Date Seed Byproducts	Walnut Shell Byproducts
ELR (N+IM)/R	[2.27E+20 (Table 5-1) + 1.87E+20 (Table 5-1)+2.52E+16 (Table 5-3)+ 5.56E+17 (Table 5-10)] / 2.18E+19 (table 5-1) =4.15E+20/2.18E=19 =19	[1.95E+20 (Table 5-2) + 1.53E+20 (Table 5-2)+1.50E+17 (Table 5-4)+ 1.38E+18 (Table 5-15)] / 3.81E+19 (table 5-2) =3.50E+20/3.81E+19 =9
EYR (R+N+IM)/IM	[(2.18E+19 (table 5-1) +2.27E+20 (Table 5-1) +1.87E+20 (Table 5-1) +2.52E+16 (Table 5-3) + 5.56E+17 (Table 5-10)] / [(1.87E+20 (Table 5-1) +2.52E+16 (Table 5-3) + 5.56E+17 (Table 5-10)] =4.36E+20/ 1.87E+20 =2.33	[3.81E+19 (table 5-2) +1.95E+20 (Table 5-2)+1.53E+20 (Table 5-2) +1.50E+17 (Table 5-4)+ 1.38E+18 (Table 5-15)] / [(1.53E+20 (Table 5-2) +1.50E+17 (Table 5-4)+ 1.38E+18 (Table 5-15)] = 3.88E+20/ 1.54E+20 =2.52
ESI	2.33/19	2.52/9

(EYR/ELR)	=0.12	=0.28
EIR (IM/ (R+N))	[1.87E+20 (Table 5-1) +2.52E+16 (Table 5-3)+ 5.56E+17 (Table 5-10)]/ (2.18E+19 (table 5-1) +2.27E+20 (table 5-1)) =1.87E+20/ 2.49E+20 =0.75	[(1.53E+20 (Table 5-2) +1.50E+17 (Table 5-4)+ 1.38E+18 (Table 5-15)]/ 3.81E+19 (table 5-2) +1.95E+20 (Table 5-2) =1.54E+20/ 2.33E+20 =0.65

N: emergy of non-renewable resources, R: emergy of renewable resources, IM: emergy of purchased resources.

From the NRDT perspective, an overview of the initial results provides some insights into how the two systems are operating in terms of their dependence on the natural system. Based on the results, the date seed by-product supply chain illustrated a high dependence on non-renewable resources, which indicates that the system is highly susceptible to natural environment impacts. Specifically, due to such heavy reliance on non-renewable resources, disruptions of the supply chain's operations are more likely to occur as a result of the scarcity of the natural non-renewable resources (e.g., groundwater), especially if these resources are critical to the system's operations (Tashman, 2011). The walnut shell supply chain, on the other hand, is less dependent on non-renewable resources. This indicates that the operations of cultivating walnuts are not highly impacted by the natural environment. More elements of the NRDT will be reviewed and discussed in Chapter 7 in light of the obtained results.

However, the initial results also indicate that the transportation of date seed is more sustainable than that of walnut shell, given that the latter has a higher UEV, meaning that more energy is required to transport walnut shells from the US to Saudi Arabia.

Initial results also indicate that some of the hypotheses developed in Chapter 3, Section 3.4, may not be supported. Above all, given the scale of the performed emergy calculations and the level of detail presented in this chapter without aggregating the results using certain emergy measures, it is difficult to assess the performance of the supply chains under study.

The emergy evaluations conducted in this chapter (Section 5.1) will be extended and replicated into system dynamics (SD) modeling to test the impact of several policies on date cultivation activities. The emergy SD model will be presented in Chapter 6. Results of the emergy evaluations of each step of the supply chain will be aggregated using emergy-based indicators, which will be presented and discussed in Chapter 7.

CHAPTER 6 : EVALUATING POLICY IMPLICATIONS USING EMERGY SYSTEM DYNAMICS

The first section of this chapter (Section 6.1) provides the structural underpinnings of the emergy system dynamics (SD) model (methodology), and the subsequent problem identification appears in Sections 6.2. Then, the variables and the conceptual model for the simulated evaluation are presented in Section 6.3. Next, in Section 6.4, the conceptual model is translated into an actual model, and a detailed representation of the model's underlying structure is presented. Section 6.5 provides a list of tests performed to validate the constructed emergy SD model and increase confidence in the model's structure. Section 6.6 introduces the policy interventions, or the evaluation of the model under various situations. These interventions will be theoretically evaluated based on the hypotheses developed in Chapter 3, Section 3.2. This chapter concludes with Section 6.7, which contains a representation of the model's simulations under various scenarios that are meant to evaluate Research Question 2 and Hypotheses 6 and 7.

6.1 The System Dynamics Methodology and Model

SD has been used for environmental assessments to model complex emergy systems at a macro level, as presented in Chapter 2, Table 2-2. This study addresses the knowledge gap surrounding emergy analysis (EA) and SD for circular supply chain decisions by developing an emergy system dynamics model using the "Structural Thinking, Experiential Learning Laboratory with Animation," or STELLA software (Richmond, 1985). The model represents the upstream tier of Saudi Aramco's date seed by-product supply chain, tying it to policymaking so that different policy scenarios can be tested. The specific research question to be addressed is: *How does* *government policy play a role in natural resource dependency (organizational decisions) in a supply chain by-product (CE) setting?*

The SD model is based on the emergy system presented in Section 5.1. The relationships between the model's variables are a replication of the emergy system of the date cultivation phase within the multitier date seed by-product supply chain. These relationships are built using a set of emergy calculations found in the EA literature (Brown and Ulgiati, 2004; Odum and Odum, 1980; Odum, 1988, 1996; Odum et al., 1995), which provides a template of all the inputs (e.g., renewable, non-renewable, and purchased resources) included in the emergy evaluation (Ulgiati and Brown, 2014), as shown by Figure 2-2 in Chapter 2.

The methodology investigates the environmental impact of various policies on the date cultivation activities of the date seed by-product supply chain using emergy-based indicators and policy intervention. The SD emergy inputs for this study are presented in Chapter 5, Section 5.1. A high-level causal loop diagram (CLD) is used to show the initial relationships between variables. The CLD is a visual representation of the investigated system that conceptualizes the model based on the structure of feedback loops, which are formed depending on the causal relationships between identified variables (Forrester, 1994; Randers, 1980).

Constructing the stock and flow diagrams represents the basis of the SD model, mathematically linking all variables using emergy-based equations. Stock and flow diagrams are developed to deal with both the conceptual and computational aspects of the investigated system using simulation modeling (Wolstenholme, 1999). They are also used to represent variables that affect the behavior of a particular system. In essence, the model structure consists of stocks, flows, auxiliaries, and connectors.

Next, the model is tested and validated using standard SD testing procedures and simulation for further structural and behavioral validation of the presented model. Finally, the policies are implemented and tested through a series of simulation runs and by tracking the model's behavior over time.

The framework shown in Figure 6-1 illustrates the modeling steps of the SD methodology (Saeed, 1994). The following sections (6.2, 6.3, 6.4, 6.5, 6.6, and 6.7) provide in-depth discussions of each step with reference to the emergy evaluation conducted in Chapter 5, Section 5.1. The next section identifies the problem.

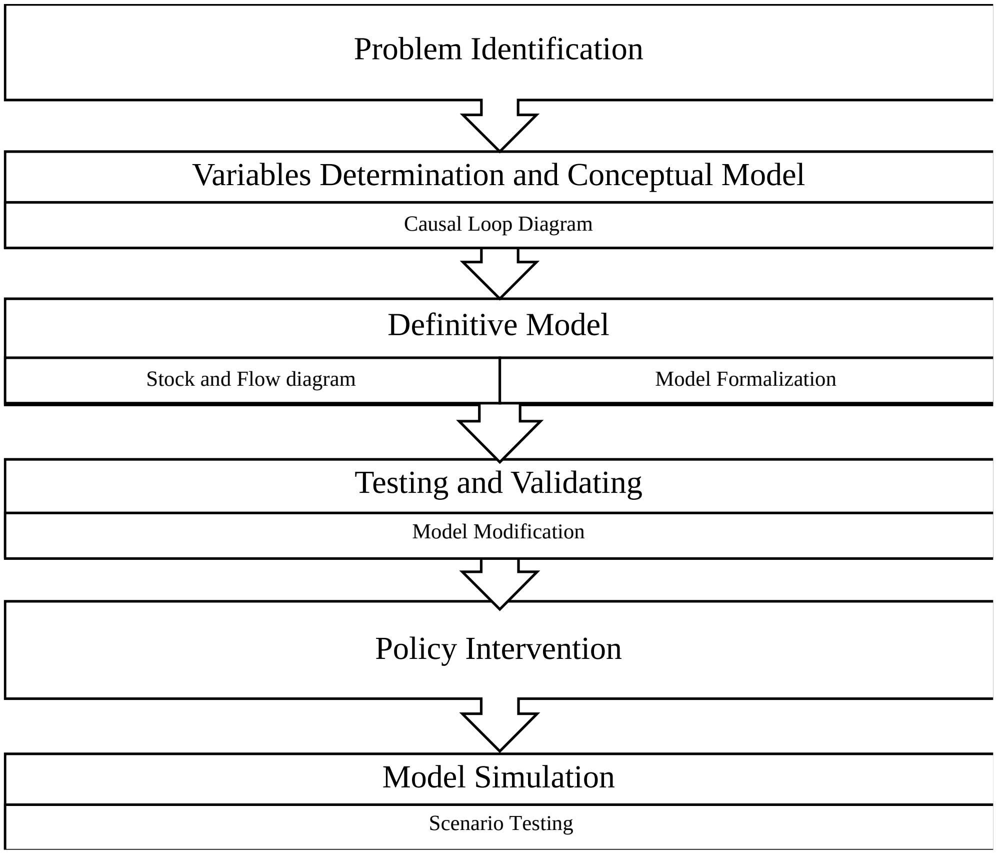


Figure 6-1: System Dynamics Methodological Framework

The following section presents the problem identification.

6.2 Problem Identification

From a supply chain perspective, different government policies may affect the operations of the by-product under study. SD modeling with EA will be used to test the policy analysis and hypotheses by evaluating several scenarios. Specifically, the second research question, *How does government policy play a role in natural resource dependency (organizational decisions) in a supply chain by-product (CE) setting?* will be answered in this chapter. The specific hypotheses, based on NRDT and given in Chapter 3, Section 3.2 are:

- *Hypothesis 6: The percentage of non-renewable resources used in the date supply chain is lower due to the impact of a government subsidy policy.*
- *Hypothesis 7: The environmental pressure is reduced as a result of Saudi Arabia's regulatory environmental actions.*

These hypotheses will be tested using emergy indicators that assess the performance of the system under study in response to policy interventions.

The boundary of the SD model is limited to the upstream supply chain of date production, which represents date cultivation operations. This is because, from an emergy perspective, the greatest contribution to the total emergy of the date seed by-product supply chain comes from the processes of date cultivation, as this is the major phase of the supply chain that includes the greatest use of natural resources (renewable and non-renewable). Another reason for this focus is that the scope of the policy interventions tied to this study are closely tied to regulating agricultural practices, which focus on the use of natural resources and most acutely influence the upstream supply chain. The ripple effect of governmental initiatives may have less influence on other supply chain tiers, where organizational decisions concern sourcing alternatives from a broader perspective (Lee et al., 2014).

The model’s behavior in a steady state reflects the emergy evaluations performed in Chapter 5, Section 5.1, Table 5-1. As we shall see in the design of the models and their execution, scenarios are simulated using SD and EA both with and without policy interventions. This design will help assess the behavioral and performance changes over time induced by governmental policies.

Four scenarios are evaluated to investigate policy interventions and their implications over time. The first scenario is the baseline for the following tested scenarios. The second scenario deals with government subsidy (P1), whereby agricultural funds are offered to encourage certain practices (Agricultural Development Fund, 2019; Royal Decree No. M/9, 2009). The third scenario investigates the effectiveness of environmental pressure (P2) (Royal Decree No. M/66, 2015) in improving the system’s performance from an emergy viewpoint. Finally, in the fourth scenario, both policies are incorporated into one simulation run to facilitate analysis of their impact on improving the used emergy indicators over time. Drawing on the NRDT, SD modeling and simulations are used to test policies that might increase or decrease uncertainty and dependencies regarding the utilization of date seed by-products.

6.3 Variable Determination and Conceptual Model

The conceptual model is a mental model that depicts the core feedback map, which represents the aggregate causal relationships between main modules (Saeed, 2022). These relationships are a replication of the relationships included in the emergy evaluations of the date cultivation activities presented in Chapter 5, Section 5.1, Table 5-1. Thus, the variables included in the model are determined based on all the inputs (resources) used in date production. Several feedback loops are constructed generating the model's dynamic behavior. The CLD is shown in Figure 6-2.

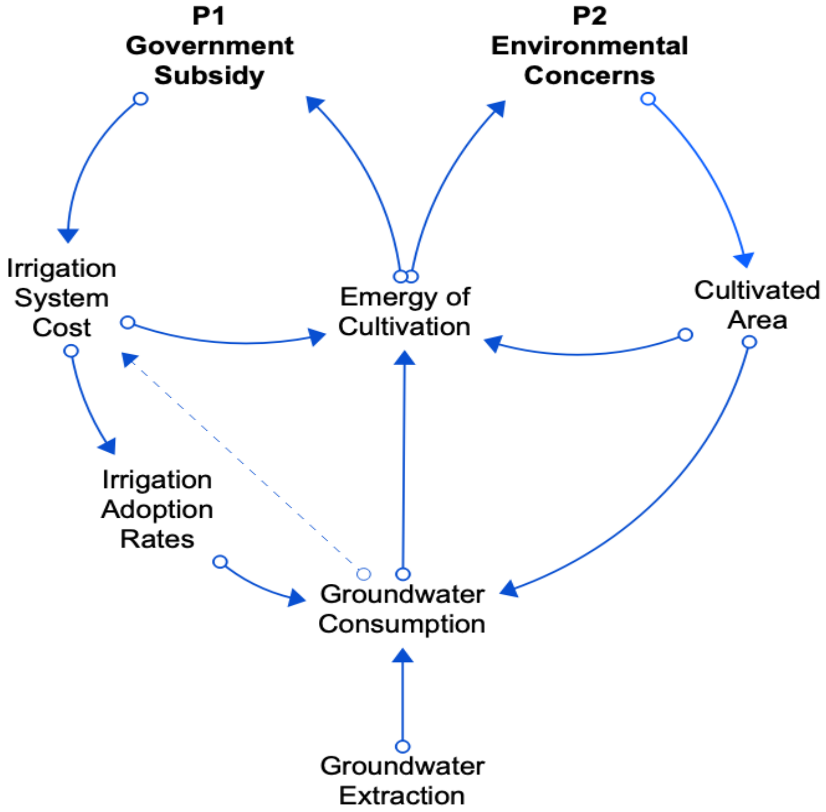


Figure 6-2: Casual Loop Diagram of the Emergy System of the Date Cultivation Supply Chain

The connections exhibited in Figure 6-2 are established according to the EA system language founded by Odum (1996) and the emergy template table provided by Ulgiati and Brown

(2014) (Figure 2-2), which serve as guidelines for emergy calculations. Emergy of Cultivation represents all the inputs to the emergy of date production supported by official government records of local agricultural production and the current literature (Al-Amoud et al., 2012; Al-Khayri et al., 2015; Almutawa, 2022; Food and Agriculture Organization of the United Nations, 2020; Kassem, 2007; The National Center for Palms and Dates, 2016, 2018a). Inputs to the model include Local Renewable Resources (R), Local Non-renewable Resources (N), Purchased (imported) Resources (IM), and Labor and Services (L&S). Each of these is modeled in a separate sub-module within the Emergy of Cultivation module. Detailed calculations of all system inputs are listed in Chapter 5, Section 5.1, Table 5-1. The Emergy of Cultivation module represents the core structure in which the emergy of the system is calculated. In addition to the sub-modules of all the system's inputs, the Emergy of Cultivation module includes a sub-module of the performance metrics, Emergy Indicators, used in the emergy evaluation of the date cultivation, which will be presented later in this dissertation at Chapter 7.

The harsh climate of the Arabian Peninsula poses a tremendous challenge to the development of the agricultural sector, making it hard to thrive without governmental support (Erskine et al., 2004). To investigate the hypotheses, the Emergy Indicators sub-module provides emergy performance metrics to determine the impact of government policies (P1 and P2) as intervention measures. We now describe these interventions as part of the evaluation.

The Saudi government supports the date production sector through the Agricultural Development Fund (Agricultural Development Fund, 2019). These funds represent a range of agricultural aid for farmers within the date industry to assist in financing agriculture-related activities. The funds, for example, include financing agricultural equipment and machinery, as well as facilitating agricultural production marketing processes in both local and international markets (Agricultural Development Fund, 2019). In the proposed model, the P1 Government Subsidy module is linked directly to the Irrigation System Cost module. The focus on irrigation techniques utilized within the date industry is driven by its direct link to water scarcity issues in Saudi Arabia (Alkolibi, 2002), thereby establishing the relationship between the P1 Government Subsidy module and the Irrigation System Cost module. Furthermore, based on the National Vision 2030 (SAV2030), the recent agricultural strategy promotes the use of modern irrigation techniques as a conservation plan for non-renewable water resources (e.g., groundwater) (Ministry of Environment Water and Agriculture, 2018a). The link between the two modules reflects the fact that the cost of irrigation systems is influenced by Agricultural Development Fund (2019) subsidies.

The Irrigation Adoption Rates module represents a dynamic structure for the adoption of each irrigation system (flood irrigation and drip irrigation). According to recent statistics published by The General Authority for Statistics (2018), approximately 49.7% (58,587 hectares) of the cultivated area uses flood irrigation systems, while 50.3% (59,294 hectares) uses drip irrigation systems, which are recommended to avoid over-exploiting non-renewable groundwater (Agricultural Development Fund, 2019). With costs decreasing due to subsidies, it is expected that the adoption rate would increase; alternatively, increases in costs or the absence of any subsidies would likely lead to a lessened adoption rate.

Because drip irrigation systems are regarded as a modern irrigation system with higher water efficiency, consuming less water per tree (Ministry of Environment Water and Agriculture, 2018a; Oosterhuis, 2023), their implementation cost is subsidized to encourage adoption (Agricultural Development Fund, 2019). As a result, the SD conceptual model suggests a causal link between drip irrigation costs and diffusion. In other words, the cost of implementing drip irrigation varies with the proportion of total cultivated area that is being irrigated using this technique.

The following causal relationship links the Irrigation Adoption Rates module with the Groundwater Consumption module. Because the amount of groundwater consumed differs based on the irrigation technique implemented (Chapter 5, Section 5.1, number 6) (The National Center for Palms and Dates, 2018b), the distribution of land between flood and drip irrigation determines the total amount of groundwater consumed. Greater use of drip due to greater adoption rates will mean that groundwater consumption is decreasing due to the efficiencies of the new technology.

The Groundwater Consumption module is linked to the Groundwater Extraction module, reflecting the main source of groundwater used for irrigation of cultivated area under date palm trees. The relationship indicates that consumption of groundwater is controlled through the dynamics of the groundwater reservoir and its storage capacity, which have been modeled within the Groundwater Extraction module (Picardi and Seifert, 1977); this module acts as a structure to limit the use of groundwater in irrigating date palm trees.

The Saudi government released a national strategy to increase the production of dates to achieve food self-sufficiency and increasing date exports (MEWA, 2020). Because dates are one of the main crops produced in Saudi Arabia, with a cultivated area of 1.18E+09 m^2 (The General Authority for Statistics, 2020), agricultural practices associated with their production raise some serious environmental concerns (Almutawa, 2022). Therefore, the P2 (Environmental Concerns) module at the top of Figure 6-2 is created to reflect date production-related environmental concerns in Saudi Arabia caused by the expansion in the cultivated area of date palm trees.

If the expansion in date production causes increasing environmental concerns about Saudi Arabia's ecological system, the government can seek to mitigate the threat by imposing a measure to reduce the cultivated area. Indeed, the Saudi government has imposed a policy that curbs water use by suspending wheat and fodder cultivation (Ministry of Environment Water and Agriculture, 2018a; Royal Decree No. M/66, 2015). Thus, the relationship between the P2 Environmental Concerns module and the Cultivated Area module is established.

The emergy equation for groundwater consumed is determined directly based on the size of the cultivated area (Chapter 5, Section 5.1, number 6); the other causal relationship impacting the Groundwater Consumption module, as shown in Figure 6-3, is the Cultivated Area module.

The final causal relationship in the SD conceptual model (Figure 6-3) closes the major feedback loop by linking the Groundwater Consumption module by the Emergy of Cultivation module. Following the fundamentals of EA calculations (Odum, 1996; Ulgiati and Brown, 2014), this relationship is based on the emergy evaluations performed in Section 5.1 (number 6) to convert the groundwater to emergy equivalent value, as groundwater is one of the major non-renewable resources used in the date production system.

Depending on the level of complexity, the model generates a large number of feedback loops that result in its dynamic behavior. These feedback loops can be either positive (reinforcing) (denoted *R* or +) or negative (balancing) (denoted *B* or -). The difference between them can be determined by tracking the original behavior of the model. If the feedback loop reinforces the original behavior, it is a positive loop; if it reverses the original behavior, it is a negative loop (Sterman, 2000, p. 144).

Explaining the relationships between variables within each module in Figure 6-2 helps in determining the major feedback loops that will be generated by simulation runs and, thus, the model's expected behavior. We will review only the major feedback loops that are used in this study and based on Figure 6-2. A review of these feedback loops will also show how emergy performance values are integrated as well as their relationships to various activities associated with cultivating dates. A simplified CLD of the date cultivation emergy system is presented in Figure 6-3 below.

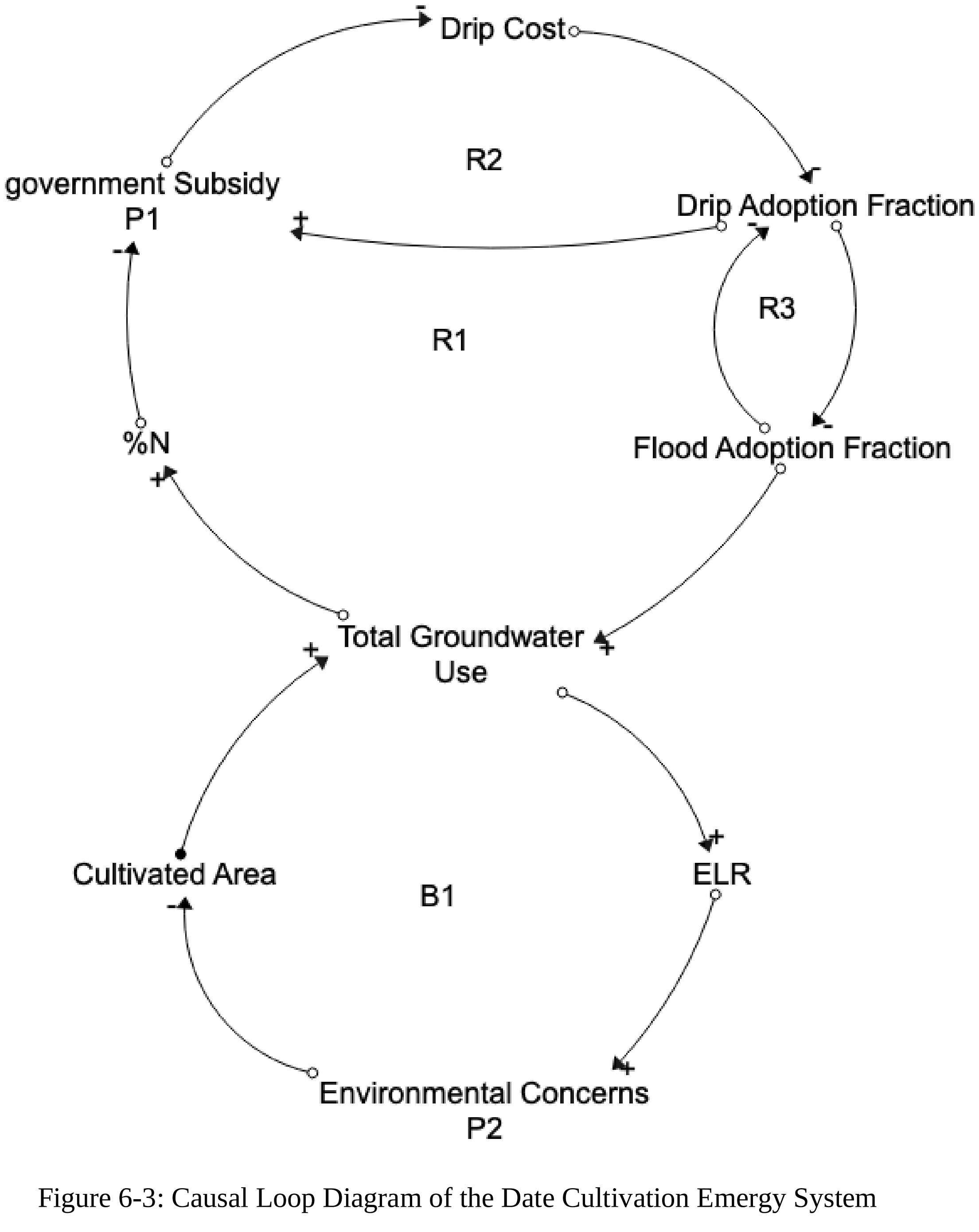


Figure 6-3: Causal Loop Diagram of the Date Cultivation Emergy System

Let us begin with the P1 Government Subsidy module to describe and explain the logic of the R1 loop. When the government offers subsidies for modern irrigation systems, such as drip irrigation in this case (Agricultural Development Fund, 2019), farmers are financially motivated to adopt these systems, which increases the drip adoption fraction. As more farmers shift to drip irrigation, the flood adoption fraction decreases, causing a decline in total groundwater use due to the shift toward water-efficient systems. This decline improved the emergy indicator of non-renewable emergy percentage (*%N*) by reducing the number (amount) of non-renewable resources used in date production, which motivates the government to continue subsidizing drip irrigation systems to reduce the consumption of groundwater.

R2 indicates that as the drip adoption fraction keeps increasing, more subsidies are offered, instigating higher adoption of drip irrigation among farmers in the date production industry. The third reinforcing loop, R3, suggests that as the drip adoption fraction increases and drip irrigation becomes more financially feasible, flood irrigation adoption declines.

The lower portion of Figure 6-3 represents the first balancing loop B1. This loop suggests that when the total groundwater use declines, the emergy loading ratio (ELR) decreases, which means that the environmental pressure caused by date cultivation operations is lower, thereby reducing the government's environmental concerns (P2). When environmental concerns regarding the consumption of natural non-renewable resources decrease, the government authorizes the expansion of the cultivated area for dates as part of its 2030 agenda of increasing date production to contribute significantly to the country's food security strategy and increase date exports (Food and Agriculture Organization of the United Nations, 2020; The General Authority for Statistics, 2020). In this loop, B1, the total consumption of groundwater is a function of the cultivated area, meaning that with the expansion of the cultivated area, total consumption of groundwater increases

(Tehrani et al., 2012). Another study by Naderi et al. (2021) used SD to test several policies, including the management of cultivated area to reduce water stress caused by agricultural activities. The researchers found that reducing the cultivated area results in a decline in water consumption, which eases the level of environmental pressure. Therefore, B1 is supported by historical data and previous published studies.

Overall, the causal relationship between government policies and agricultural development has been highlighted in a number of SD studies (Tehrani et al., 2012).

6.4 Definitive Model Structure

The structure of the model is a replication of the emergy system provided in Section 5.1 with reference to the emergy calculations presented in Table 5-1, following emergy system language (Odum, 1988, 1996; Odum et al., 1995). The model structure, including the relationships between the constructing parameters, is based on the concept of emergy system modeling language proposed by Odum and Odum (2000). To depict a complex real-world system, hierarchical representations of the model's core components are utilized, with the inclusion of subsystems to disaggregate complex dynamic relationships (Meadows, 2008, p. 83).

The model is divided into six primary modules, two policy intervention modules, and five sub-modules, each of which is structured to include a set of variables, flows, constants, and graphical functions. This section offers an in-depth review of each module, outlining its underlying structure. The model's boundary includes agricultural activities taking place on date farms located in Saudi Arabia, excluding private farms. Although the emergy evaluation performed in this dissertation research extends over a multitier supply chain, the main focus of the SD model is limited to the cultivation of dates, which is the main source of the evaluated date seed by-products.

6.4.1 Emergy Cultivation Module

The core module in this model is Emergy Cultivation, which includes five sub-modules: Renewable Resources Emergy, Non-renewable Resources Emergy, Purchased Resources Emergy, L&S Emergy, and Emergy Indicators. The Emergy Cultivation module focuses on the evaluation of the agricultural aspects of date production, which represents the first tier of the date seed supply chain.

The Renewable Resources Emergy sub-module is constructed to include the energy of all the renewable resources that are contributed toward producing dates, including rain, wind, heat, and sun. The relationships between parameters are built on the notion and language of the emergy system (Odum, 1996). Each renewable resource is represented by a stock of accumulated energy, which is fed by an inflow of the resource energy and is depleted through an energy loss outflow controlled by an energy loss rate for each renewable resource. Resources' energy inflows are determined using energy calculations found in the literature (Odum, 1996). Each energy source possesses a fraction of available energy, creating a parameter of useful energy that is available to do work of a higher value, which is multiplied by a conversion factor (UEV) extracted from the emergy literature and referenced in the emergy evaluation in Section 5.1 Table 5-1. All of the inflows in the Renewable Resources Emergy sub-module are multiplied by the stock of the cultivated area ghosted from the Cultivated Area module. The stock and flow structure, along with the equations of the Renewable Resources Emergy sub-module variables, are shown in Figure 6-4 and Table 6-1 below. The emergy calculations of each renewable resource are presented in Section 5.1, numbers 1–4.

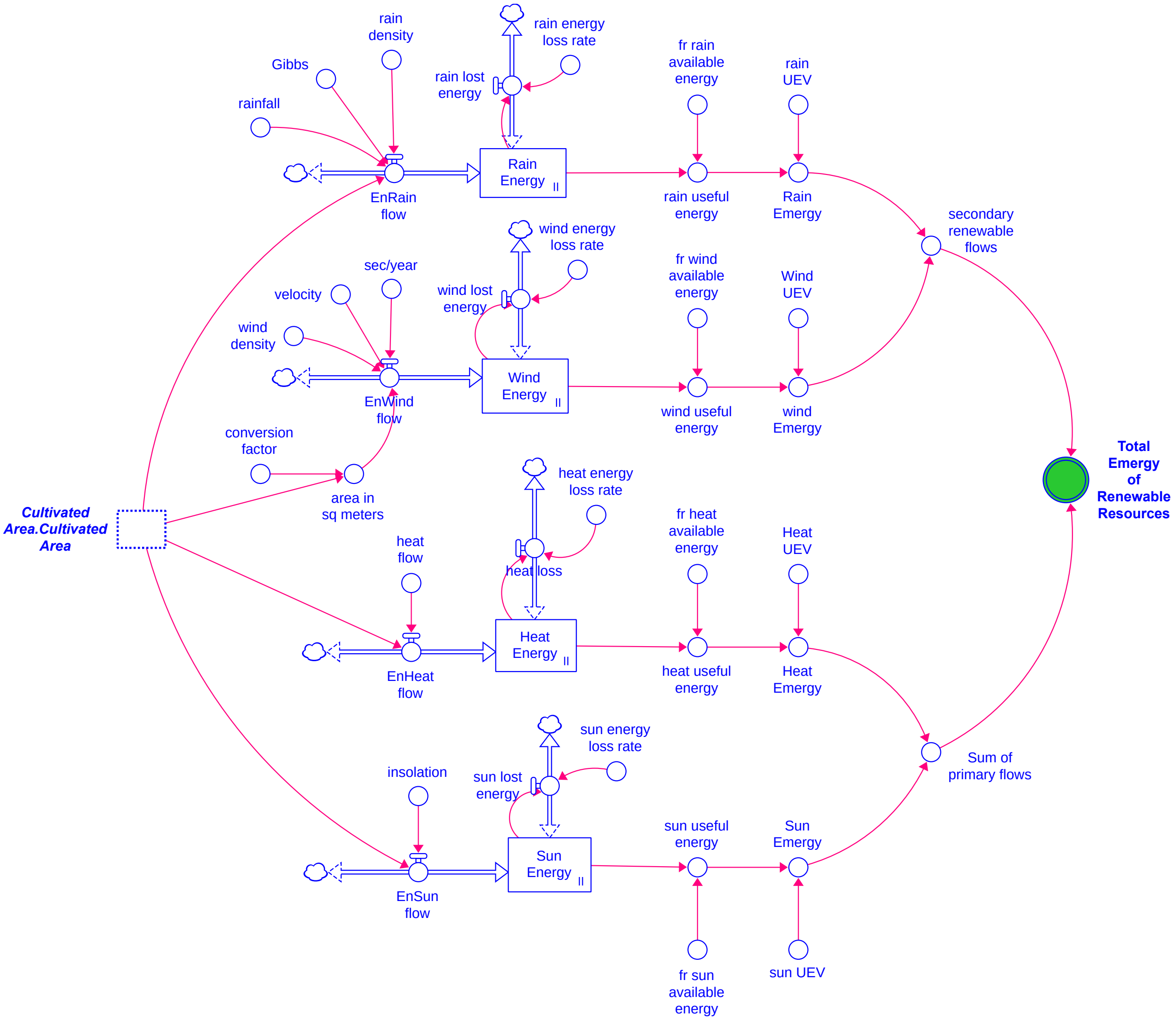


Figure 6-4: Stock and Flow Diagram of the Emergy of Renewable Resources

Table 6-1: Renewable Resources Emergy Module Equations

Variable	Equation	Properties	Units
Renewable Resources Emergy			
Heat Energy(t)	Heat Energy (t - dt) + (EnHeat flow – heat loss) * dt	INIT Heat Energy = 2.30E+14	joule
Rain Energy(t)	Rain Energy(t - dt) + (EnRain flow – rain lost energy) * dt	INIT Rain Energy = 1.34E+14	Joule

Sun Energy(t)	Sun Energy(t - dt) + (EnSun flow – sun lost energy) * dt	INIT Sun Energy = 9.52E+18	joule
Wind Energy(t)	Wind Energy (t - dt) + (EnWind flow – wind lost energy) * dt	INIT Wind Energy = 1.29E+16	joule
EnHeat flow	Heat flow*Cultivated Area. Cultivated Area*0.095		Joule/Years
EnRain flow	(Cultivated Area. Cultivated Area*rain density*rainfall*Gibbs)		Joule/Years
EnSun flow	Cultivated Area. Cultivated Area*insolation*(1-0.31)		Joule/Years
EnWind flow	Area in sq meters*velocity*wind density*"sec/year"*1.64 E-03		Joule/Years
Heat loss	Heat energy loss rate*Heat Energy		Joule/Years
Rain lost energy	Rain Energy*rain energy loss rate		Joule/Years
Sun lost energy	Sun Energy*sun energy loss rate		Joule/year
Wind lost energy	Wind energy loss rate*Wind Energy		Joule/year
Area in sq meters	Cultivated Area. Cultivated Area*conversion factor		square meter
Conversion factor	10000		square meter/hectare
Fr heat available energy	1		1/year
Fr rain available energy	1		1/year
Fr sun available energy	1		1/year
Fr wind available energy	1		1/year
Gibbs	4.72		joule/gram
Heat Emergy	Heat useful energy*Heat UEV		sej/year
Heat energy loss rate	1		1/year
Heat flow	2.05E+10		joule/hectare/year
Heat UEV	4.90E+03		sej/joule
Heat useful energy	Fr heat available energy*Heat Energy		Joule/year
insolation	1.17E+14		joule/hectare/year
Rain density	1E+6		gram/cubic meter
Rain Emergy	Rain UEV*rain useful energy		sej/year
Rain energy loss rate	1		1/year

Rain UEV	7.00E+03		sej/joule
Rain useful energy	Rain Energy*fr rain available energy		Joule/year
rainfall	300		cubic meter/hectare/year
"sec/year"	3.154E+07		second/year
Secondary renewable flows	MAX (Rain Emergy, wind Emergy)		sej/year
Sum of primary flows	Heat Emergy +Sun Emergy		sej/year
Sun Emergy	Sun useful energy*sun UEV		sej/year
Sun energy loss rate	1		1/year
Sun UEV	1		sej/joule
Sun useful energy	Fr sun available energy*Sun Energy		Joule/year
Total Emergy of Renewable Resources	Secondary renewable flows +Sum of primary flows		sej/year
velocity	(5.7) ^3		cubic meter/second^3
Wind density	1.23		kg/cubic meter
Wind Emergy	Wind useful energy*Wind UEV		sej/year
Wind energy loss rate	1		1/year
Wind UEV	8.00E+02		sej/joule
Wind useful energy	Fr wind available energy*Wind Energy		Joule/year

The second sub-module is Non-Renewable Resources Emergy, which represents the available energy of the non-renewable resources used to produce dates. The structure includes two resources, soil and groundwater, both of which are transformed from energy to emergy through a set of equations derived from the emergy literature. The stock of soil energy accumulates over time due to inflowing soil energy that is determined by a specific equation in a particular area, and it is partially depleted due to energy loss over time. Then, a fraction of the soil energy is transformed into emergy by a conversion factor. Similarly, the groundwater energy accumulates over time in proportion to the volume of groundwater consumed; then, only available energy is converted to emergy through a transformation process. Finally, all of the non-renewable resources' emergy is summed to account for the total emergy on non-renewable resources. The stock and flow diagram of the Non-renewable Resources Emergy sub-module is illustrated in Figure 6-5 below, with the equations listed in Table 6-2. The emergy calculations for each non-renewable resource are presented in Section 5.1, numbers 5 and 6.

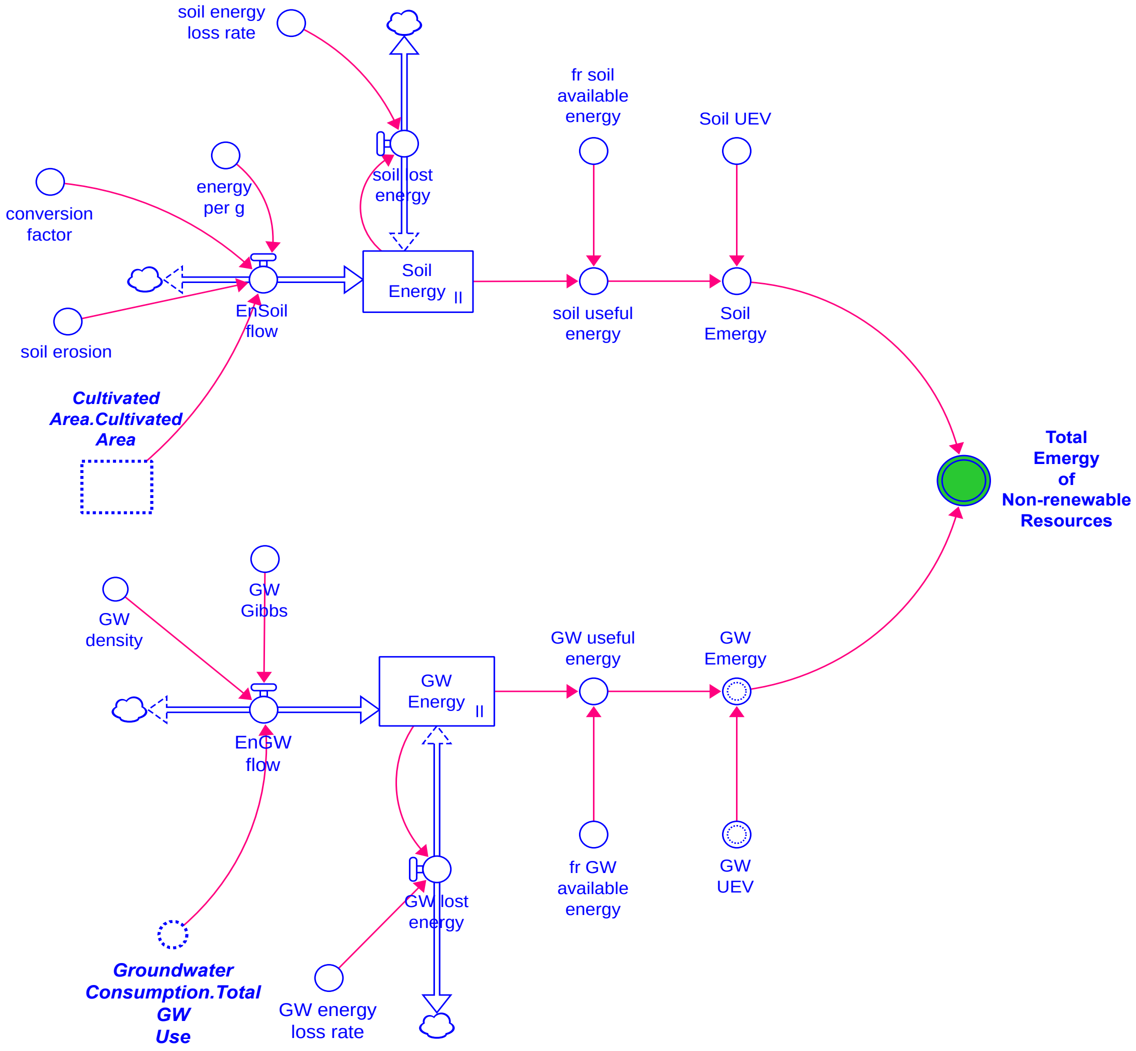


Figure 6-5: Stock and Flow Diagram of the Emergy of Non-renewable Resources

Table 6-2: Non-renewable Resources Emergy Module Equations

Variable	Equation	Properties	Units
Non-renewable Resources Emergy			

GW Energy (t)	GW Energy(t - dt) + (EnGW flow – GW lost energy) * dt	INIT GW Energy = 4.50E+15	Joule
Soil Energy(t)	Soil Energy(t - dt) + (EnSoil flow – soil lost energy) * dt	INIT Soil Energy = 5.84E+14	Joule
EnGW flow	GW Gibbs*GW density*Groundwater Consumption.Total GW Use		Joule/Years
EnSoil flow	Cultivated Area.Cultivated Area*soil erosion*0.015*conversion factor*energy per g		Joule/Years
GW lost energy	GW Energy*GW energy loss rate		Joule/year
Soil lost energy	Soil Energy*soil energy loss rate		Joule/Years
Conversion factor	5.4		kcal/gram
Energy per g	4186		joule/kcal
Fr GW available energy	1		1/year
Fr soil available energy	1		1/year
GW density	1E+06		gram/cubic meter
GW Emergy	GW useful energy*GW UEV		sej/year
GW energy loss rate	1		1/year
GW Gibbs	4.56		joule/gram
GW UEV	4.10E+04		sej/joule
GW useful energy	Fr GW available energy*GW Energy		Joule/year
Soil Emergy	Soil useful energy*Soil UEV		sej/year
Soil energy loss rate	1		1/year
Soil erosion	14605700		gram/hectare/year
SoilUEV	7.40E+04		sej/joule
Soil useful energy	Fr soil available energy*Soil Energy		Joule/year
Total Emergy of Non-renewable Resources	GW Emergy+Soil Emergy		sej/year

The next sub-module is Purchased Resources Emergy, which includes resources purchased from outside the system's boundary. Machinery, diesel, gasoline, and fertilizers are all purchased resources used in the plantation and cultivation of dates. These resources are added to the model as exogenous parameters summed up to yield the total emergy of purchased resources. The structure of this sub-module, as well as its equation table, are illustrated in Figure 6-6 and Table

6-3. The emergy calculations of each purchased resource are presented in Section 5.1, numbers 7–10.

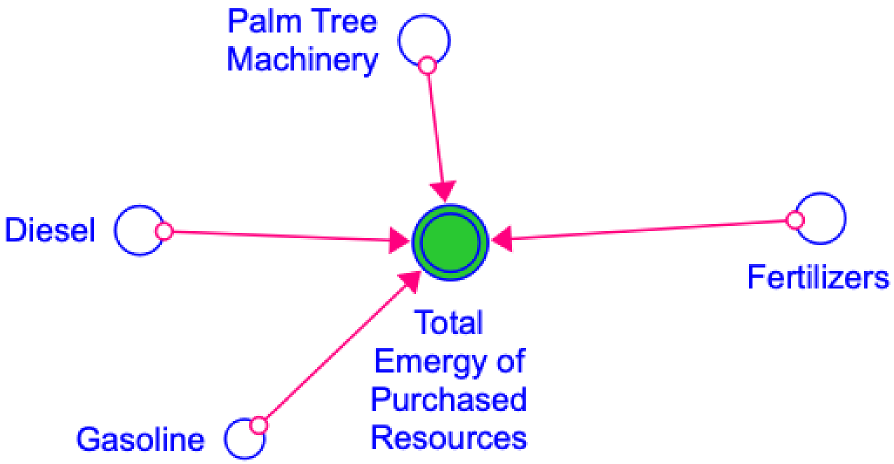


Figure 6-6: Stock and Flow Diagram of the Emergy of Purchased Resources

Table 6-3: Purchased Resources Emergy Module Equations

Variable	Equation	Units
Diesel	1.85E+16	sej/year
Total Emergy of Purchased Resources	Diesel + Gasoline + Machinery Palm Tree + fertilizers	sej/year
Fertilizers	9.59E+13	sej/year
Gasoline	1.42E+13	sej/year
Palm Tree Machinery	1.03E+18	sej/year

The final step in calculating the total emergy of date cultivation is transforming the money spent to accommodate the cost of direct labor and indirect services such as electricity, other agricultural supplies, and equipment, all of which are included within the sub-module of L&S emergy. For instance, capital expenditure and emergy of labor are implemented in the model as exogenous parameters, while the irrigation system cost is ghosted from the Irrigation System Cost module. All the money spent to facilitate the production of dates is converted to emergy using an emergy conversion factor called the "emergy-to-money ratio," which assigns money an equivalent value of solar emergy (Odum, 1996). The structure and equations of the L&S Emergy sub-module are shown in Figure 6-7 and Table 6-4 below. The L&S emergy calculations are presented in Section 5.1, numbers 11 and 12.

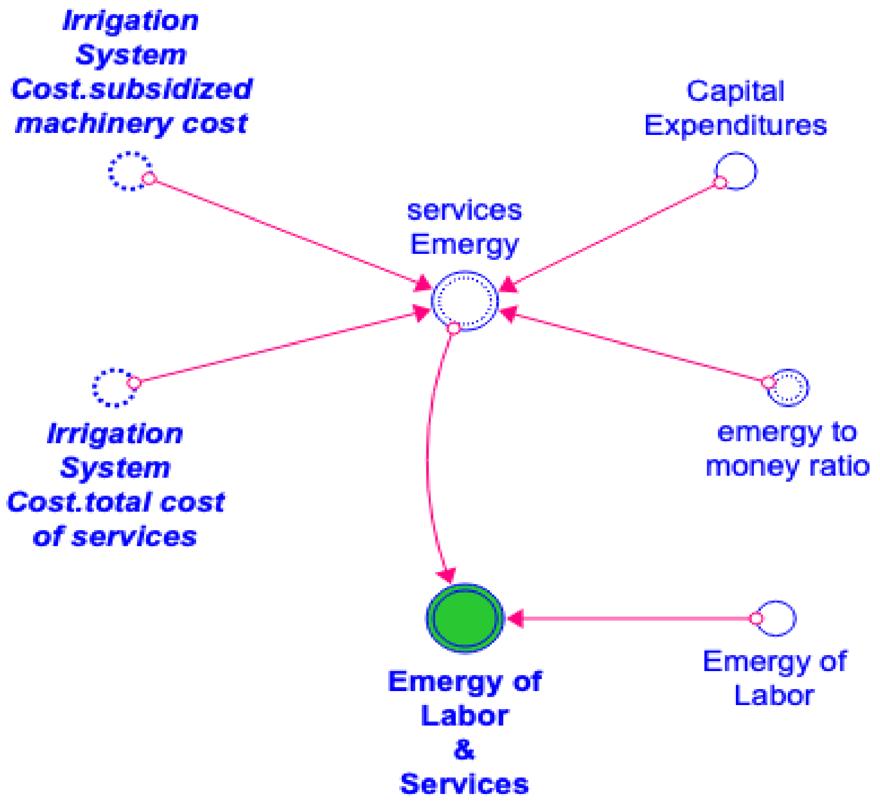


Figure 6-7: Stock and Flow Diagram of the Emergy of Labor and Services

Table 6-4: Labor and Services Emergy Module Equations

Variable	Equation	Units
Labor &Services Emergy		
Capital expenditures	987760	$/year
EmDate Labor	6.74E+16	sej/year
Emergy to money ratio	6.10E+12	sej/$
Labor & Services	Services Emergy + EmDate Labor	sej/year
Services Emergy	(Irrigation System Cost. Total cost of services+Capital expenditures + Irrigation System Cost. Subsidized machinery cost)*emergy to money ratio	sej/year

The final sub-module within the Emergy of Cultivation module is the Emergy Indicators. The SD model uses two emergy indicators: the emergy loading ratio (ELR) and the percentage of non-renewable emergy (*%N*) as an index for performance evaluation and a tool for policy interventions. These two indicators are calculated using various ratios comprising the total emergy of the system and the individual value of each sub-module's emergy. A stock and flow structure is created to account for the accumulation of the total emergy, both with and without including the emergy of L&S, with an inflow of all the resources' emergy calculated in the previous sub-modules. Moreover, the outflow demonstrates the emergy yield (output) of the system to the economy. ELR aids in measuring the level of environmental pressure caused by the system's operations; thus, a large value reflects a higher environmental pressure, while *%N* measures the contribution of the non-renewable resources' in producing the system's output. A high *%N* indicates over-exploitation of non-renewable natural resources. The sub-module structure and equations are illustrated below in Figure 6-8 and Table 6-5. The equations of the emergy based indicators are presented in Section 2.4, Table 2-1.

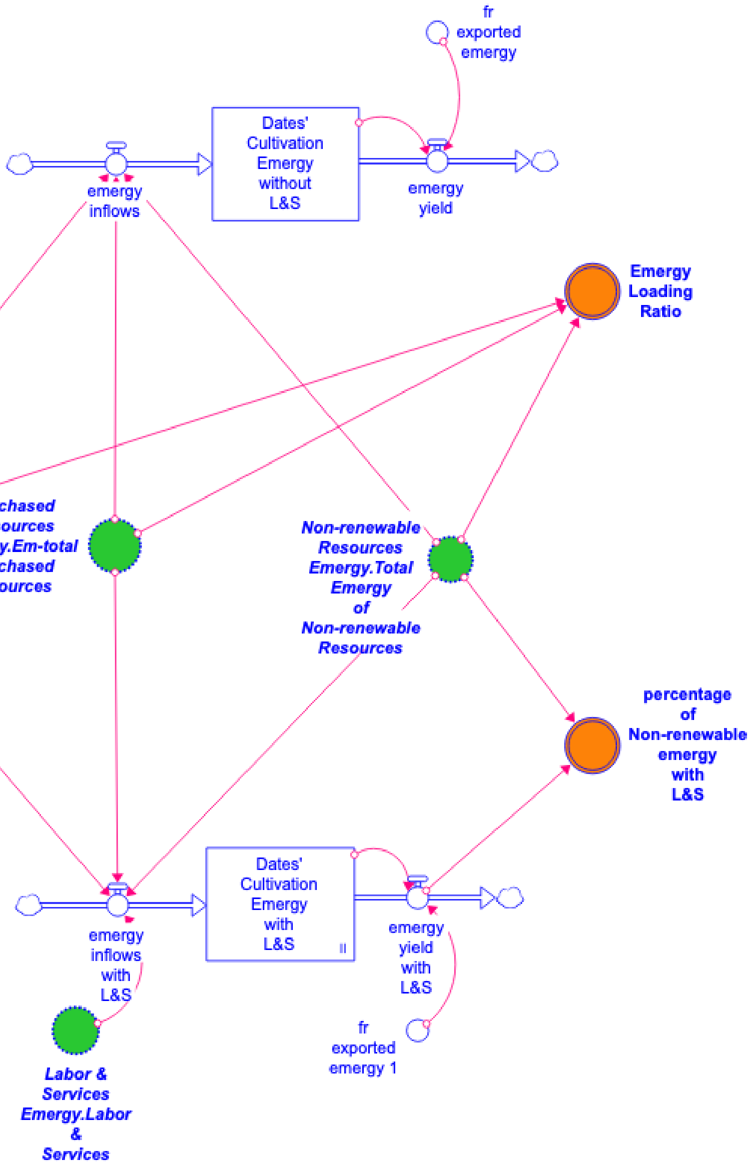


Figure 6-8: Stock and Flow Diagram of the Emergy Indicators

Table 6-5: Emergy Indicators Module Equations

	Equation	Properties	Units
Emergy Indicators			
Dates' Cultivation Emergy with L&S(t)	Dates' Cultivation Emergy with L&S(t - dt) + (emergy inflows with L&S – emergy yield with L&S) ’ dt	INIT Dates' Cultivation Emergy with L&S = 3.28’+21	sej
Dates' Cultivation Emergy without L&S(t)	Dates' Cultivation Emergy –ithout L&S (t - dt) + (emergy inflows – emergy yield) ’ dt	INIT Dates' Cultivation Emergy without L&S = 463.58E+18	sej
Emergy inflows	Renewable Resources Emergy.Total Emergy of Renewable Resources +Non-renewable Resources Emergy.Total Emergy of Non-renewable Resources+Purchased Resources Emergy.Em-total purchased resources		sej/year
Emergy inflows with L&S	Renewable_Resources_Emergy.Total_Emergy_of_Renewable_Resources+"Non-renewable_R”s”urces_Emergy"."Total_Emergy_of_Non-rene”able_Resources"+Purchased_Re”ources_Emergy."Em-total_purc”ased_resources"+Labor_&_Services_Emergy.Labor_&_Services		sej/year
Eme’gy yield	Dates' Cultivation Emergy without L&S*fr exported emergy		sej/year
Emergy yield’with L&S	Dates' Cultivation Emergy with L&S*fr_exported_emergy_1		sej/year
Emergy Loading Ratio	(Non-renewable Resources Emergy.Total Emergy of Non-renewable Resources +Purchased Resources Emergy.Em-total purchased resources)/Renewable Resources Emergy.Total Emergy of Renewable Resources		Dimensionless
Fr exported emergy	1		1/year
Fr exported emergy 1	1		1/year
Percentage of Non-renewable emergy with L&S	Non-renewable Resources Emergy.Total Emergy of Non-renewable Resources"/emergy yield with L&S		Dimensionless

6.4.2 Groundwater Consumption Module

The Emergy of Cultivation module is linked by three other modules that constitute the values and dynamics of the resources included in the cultivation of dates. The Groundwater Consumption module demonstrates the structure of groundwater usage by exhibiting its dynamics as a non-renewable resource used in producing dates.

The total groundwater use (Total GW Use) is divided between two irrigation techniques—drip and flood—that are commonly adopted in date agriculture in Saudi Arabia. The consumption rate of flood irrigation per tree is higher than that of drip irrigation, making the latter a more environmentally conscious alternative. Hence, Total GW Use is determined depending on the adoption fraction of each irrigation technique along the cultivated area. Another module, Irrigation Adoption Rates, depicts the dynamics of the adoption fraction of each irrigation technique. Because the volume of groundwater consumed differs based on the implemented irrigation system, the structure of the module is built to account for each system specifically in terms of the number of date palm trees and the fraction of area for each system. In other words, the consumption of groundwater depends directly on the cultivated area, the number of date palm trees per cultivated area, the amount of water consumed per date palm tree, and the adoption rate of each irrigation system.

Total groundwater use is restricted by a graphical function (Figure 6-9) named the “groundwater availability factor,” which prevents the consumption of groundwater beyond the reservoir’s storage capacity. In other words, the groundwater availability factor drops to zero when date cultivation consumes most of the groundwater storage. The graphical function changes according to the fraction of groundwater used (Fr GW Used), which represents the ratio between the average of total groundwater use (Ave Total GW Use) and storage. The “groundwater availability factor" is an S-shaped curve with extreme points of (0,1) reflecting the entire availability of the groundwater storage when no consumption is occurring, and (1,0) demonstrating the over-depletion of groundwater storage, resulting in an extreme groundwater shortage. The inflection point (0.5,0.5) indicates a case where date production is consuming half of the storage capacity for irrigation purposes, which suggests that groundwater availability is only 50% of storage. The graphical function, the structure, and the equations of the Groundwater Consumption module are illustrated below in Figures 6-9 and 6-10 and Table 6-6, respectively. The groundwater emergy equations are presented in Section 5.1, number 5. The variables included in the structure of the module are based on data from (Ali et al., 2008; The General Authority for Statistics, 2020; The National Center for Palms and Dates, 2016, 2018b).

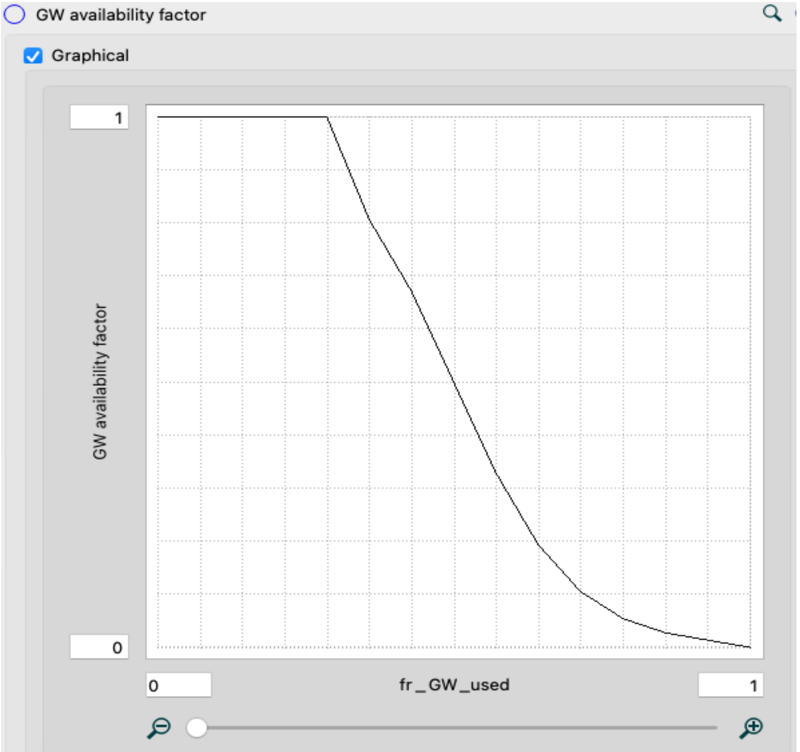


Figure 6-9: Groundwater Availability Factor Graphical Function

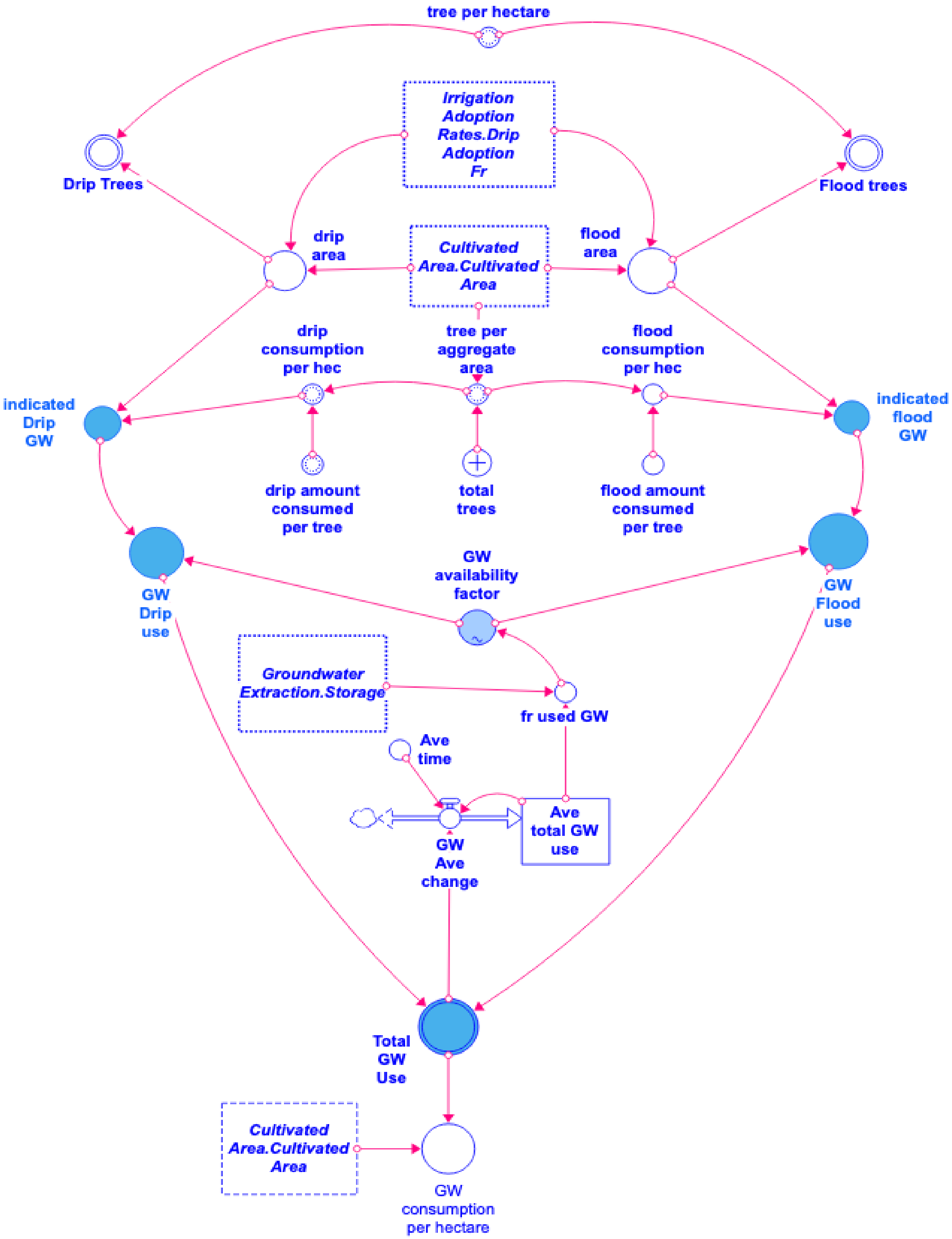


Figure 6-10: Stock and Flow Diagram of the Groundwater Consumption

Table 6-6: Groundwater Consumption Module Equations

	Equation	Properties	Units
Groundwater Consumption			
Ave total GW use (t)	Ave –otal GW use(t - dt) + (GW Ave change) * dt	INIT Ave total GW use = 986E+6	cubic meter
GW Ave change	Total GW Use-(Ave total GW use/Ave time)		cubic meters/year
Ave time	1		year
Drip amount consumed per tree	34.73		cubic meter/tree/year
Drip area	Cultivated Area. Cultivated Area*Irrigation Adoption Rates. Drip Adoption Fr		hectare
Drip consumption per hec	Drip amount consumed per tree*tree per aggregate area		cubic meter/hectare/year
Drip Trees	Drip area*tree per hectare		tree
Flood amount consumed per tree	41.99		cubic meter/tree/year
Flood area	Cultivated Area.Cultivated Area*(1-Irrigation Adoption Rates.Drip Adoption Fr)		hectare
Flood consumption per hec	Tree per aggregate area*flood amount consumed per tree		cubic meter/hectare/year
Flood trees	Flood area*tree per hectare		tree
Fr GW used	Ave total GW use/Groundwater Extraction.Storage		Dimensionless
GW availability factor	GRAPH(fr GW used) Points: (0.000, 1.000), (0.0714285714286, 1.000), (0.142857142857, 1.000), (0.214285714286, 1.000), (0.285714285714, 1.000), (0.357142857143, 0.806678630198), (0.428571428571, 0.671347453483), (0.500, 0.500), (0.571428571429, 0.328652546517), (0.642857142857, 0.193321369802), (0.714285714286, 0.10500058502), (0.785714285714, 0.0543132661326), (0.857142857143, 0.0273467867962), (0.928571428571, 0.0135769169437), (1.000, 0.000)		Dimensionless
GW consumption per hectare	Total GW Use/Cultivated Area.Cultivated Area		cubic meter/hectare/year
GW Drip use	Indicated Drip GW*GW availability factor		cubic meters/year

GW Flood use	Indicated flood GW*GW availability factor		cubic meters/year
Indicated Drip GW	Drip area*drip consumption per hec		cubic meters/year
Indicated flood GW	Flood area*flood consumption per hec		cubic meters/year
Total GW Use	GW Drip use+GW Flood use		cubic meters/year
Total trees	Drip Trees + Flood trees		tree
Tree per aggregate area	Total trees/Cultivated Area.Cultivated Area		tree/Hectares
Tree per hectare	218		trtares

6.4.3 Groundwater Extraction Module

Consumption of groundwater is controlled through the dynamics of the groundwater reservoir and its storage capacity, which have been modeled within the Groundwater Extraction module. This module acts as a structure that limits the use of groundwater in irrigating date palm trees. It highlights the flow of water from the main groundwater reservoir to the storage through extraction and consumption processes while accounting for natural annual recharge rates (Picardi and Seifert, 1977).

According to historical data, the non-renewable groundwater reservoir ranges between 259.1–760.6 billion cubic meters (BCM) (Chowdhury and Al-Zahrani, 2015). However, a more recent study indicates that the proven reservoir of groundwater is around 103.360 BCM, while the annual withdrawal rate is 20 BCM (Chandrasekharam, 2018; Chandrasekharam et al., 2017). Hence, the initial value of the groundwater stock is estimated at 103.360 BCM and the annual extraction fraction (Extraction Fr) is estimated at around 19% by dividing the annual withdrawal volume by the initial value of the groundwater stock. These values are estimated under the assumption that the structure focuses only irrigated area used for the cultivation of date palm trees, excluding other agricultural uses of the groundwater. Aside from the extraction fraction, groundwater stock is depleted using a graphical function that plots the extraction pressure against years of storage coverage to supply the agricultural demands of date production. The extraction pressure decreases exponentially as the years of storage coverage increase. The graphical function is bounded by two extreme points: the first is (2,0), where the pressure to extract more groundwater lessens as the years of storage coverage reach 2 years; the second extreme point is (0,4), where the storage years of coverage are insufficient to fulfill consumption expectations, causing the extraction pressure to rise to 4. The inflection point (1,1) represents the case where storage capacity covers groundwater consumption demands for one year, normalizing the extraction pressure at 1. As for the years of coverage, the concept behind Little's laws is adopted to reflect the rate at which the storage can be depleted (Little, 1961). The initial storage value is estimated using data from the annual agricultural statistical book published by the Ministry of Environment, Water, and Agriculture (MEWA, 2020).

According to the published statistics, the non-renewable groundwater usage for agricultural purposes in 2020 is estimated to be around 8.50E+09 cubic meters per year. Considering the current distribution of area according to the adoption of irrigation system techniques, the total groundwater consumed by date production is 9.85E+08 m^3/yr (as calculated in Section 5.1, number 6) which constitutes approximately 46% of the total groundwater consumed by all agricultural products. Thus, the initial value of the storage is estimated at 3.69E+09 m^3.

The following are illustrations of the extraction pressure graphical function (Figure 6-11) and the stock and flow structure (Figure 6-12); Table 6-7 contains the equations.

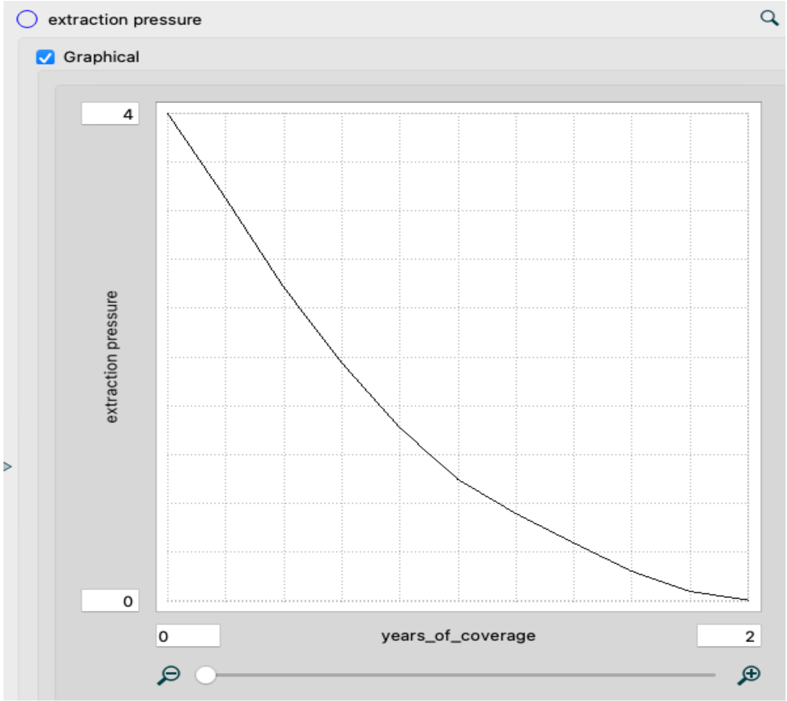


Figure 6-11: Extraction Pressure Graphical Function

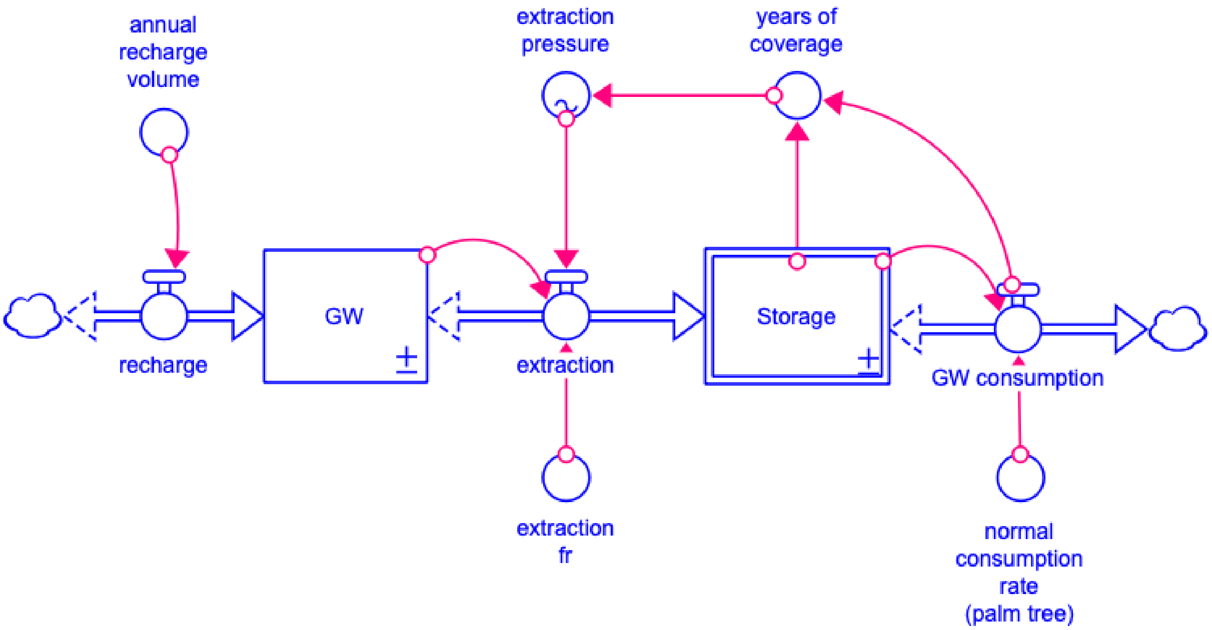


Figure 6-12: Stock and Flow Diagram of the Groundwater Extraction

Table 6-7: Groundwater Extraction Module Equations

	Equation	Properties	Units
Groundwater Extracti–n			
GW(t)	GW(t - d–) + (recharge - extraction) * dt	INIT GW = 103.360E+9	cubic meter
Storage–(t)	Storage (t - dt) + (extraction – GW consumption) * dt	INIT Storage = 3.69E+9	cubic meter
extraction	Extraction pressure*GW*extraction fr*0+GW*extraction fr		cubic meter/year
GW consu”ption	Storage*"normal consumption rate (palm tree)"		Cubic Meters/year
recharge	Annual recharge volume		cubic meter/year
Annual recharge volume	2.4E+9		Cubic Meters/year
Extraction fr	0.0232		1/year
Extraction pressure	GRAPH(years of coverage) Points: (0.000, 4.000), (0.200, 3.305), (0.400, 2.576), (0.600, 1.956), (0.800, 1.424), (1.000, 1.000), (1.200, 0.719), (1.400, 0.477), (1.600, 0.245), (1.800, 0.079), (2.000, 0.009)		Dimensionless
Normal consumption rate (palm tree)	0.650		1/year
Years of coverage	Storage/GW consumption		year

6.4.4 Irrigation adoption rates module

Irrigation Adoption Rates is another integral module affecting groundwater consumption. The stocks of the flood adoption fraction (Flood Adoption Fr) and the drip adoption fraction (Drip Adoption Fr) are linked together with two flows, creating a closed structure that fills and drains the two stocks simultaneously. The two flows reflect the conversion from one system to the other, driven by an external pressure to promote or discourage adoption of the tested irrigation methods. The closed stock-and-flow structure replicates a similar structure developed by published studies, such as (Gies et al., 2014; Reinker and Gralla, 2018). The structure of the stock and flow diagram in this module is built around the notion that adoption of certain technologies is dependent on scarcity and cost factors, as posited by (Alcon et al., 2011).

The two stocks change according to a normal conversion fraction estimated at 3.44E-07 according to historical data published by The National Center for Palms and Dates (2018b). However, there is no update on the published statistics, and using a low rate will make difficult to track changes in the model's behavior. Thus, we use estimate a 5% conversion rate based on a published study by Taylor and Zilberman (2017).

The adoption fractions are affected by the cost ratio between the two irrigation systems using two graphical functions with inverse curves to reflect that impact, shown in Figures 6-13.a and 6-13.b. The cost of sustainable technological techniques within agriculture is a driving factor that increases the adoption rate of such practices (Musango et al., 2012; Taylor and Zilberman, 2017). Because the drip technique is regarded as a modern irrigation system that consumes less water per tree, its implementation cost is subsidized. Thus, when the drip is the numerator, the cost ratio is normally less than 1.

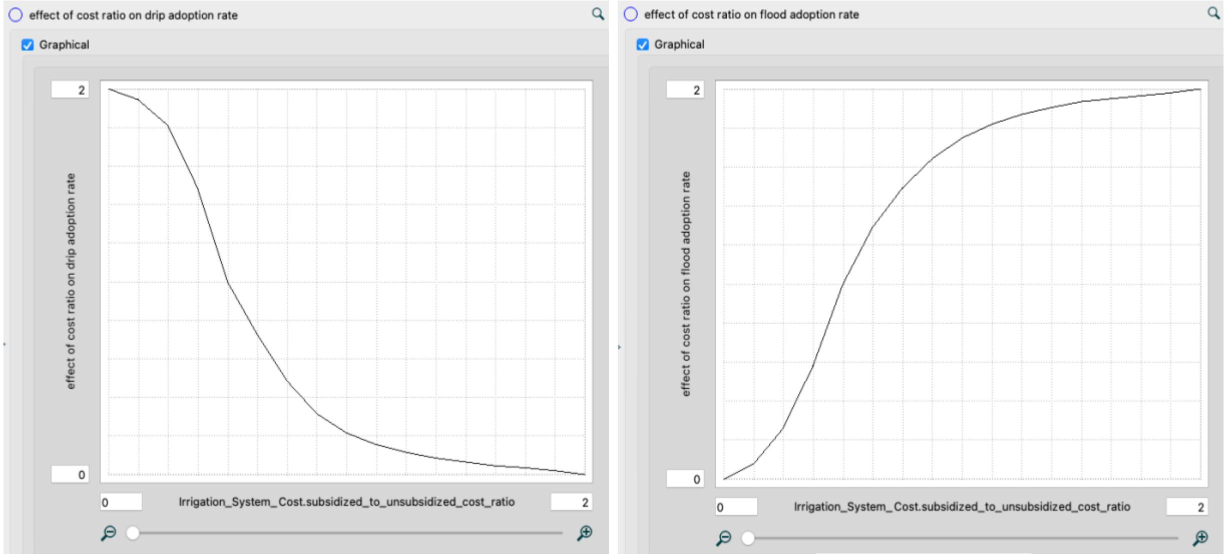


Figure 6-13. a

Figure 6-*13*. b

Figure 6-13: 6-13.a Effect of Cost Ration on Drip Rate Graphical Function, 6-13.b Effect of Cost on Flood Adoption Rate

The first graphical function (Figure 6-17.a) shows the effect of cost ratio on drip adoption rate where the *x*-axis is the ratio between the subsidized system (drip) and the nonsubsidized system (flood). The ratio of subsidized to unsubsidized costs varies depending on the percentage of subsidies offered by the government regarding the implemented irrigation system. The effect on the conversion to drip changes according to the discrepancy between the subsidized and unsubsidized cost. When the percentage of subsidy increases, the cost decreases and the ratio of subsidized to unsubsidized cost decreases proportionally, increasing the effect of converting from flood irrigation to drip irrigation. More precisely, when the cost ratio decreases as a result of the lower cost of the drip irrigation system, the probability of shifting from flood irrigation to drip irrigation is much higher, and vice versa. The inflection point (0.5,1) suggests that at the baseline scenario, when the cost of the drip irrigation system is half that of the flood irrigation system, the effect on the conversion rate to the drip system is 1, indicating that the effect is normalized at the baseline scenario. The choice of the S-shaped curve captures the behavior of modern agricultural innovation adoption patterns over time (Feder and O'Mara, 1981). The extreme point (2,0) represents a scenario where the cost of drip irrigation is twice that of flood irrigation, which makes the effect on the drip conversion rate zero. The other extreme scenario is reflected by the point (0,2), presenting a situation where the government completely subsidizes the drip irrigation system. In this case, the effect on the drip conversion rate will be doubled.

The other graphical function, effect of cost ratio on flood adoption rate, reverses the behavior of Figure 6-17.b with the same *x*-axis variable, subsidized to unsubsidized cost. The *y*-axis represents the effect of the cost ratio on flood adoption rate, which affects the conversion from drip to flood irrigation. The conversion from drip to flood irrigation changes according to the percentage of subsidy provided by the government. When the subsidy decreases, the cost of drip irrigation increases gradually to match the cost of flood irrigation. In this particular case, the attractiveness of adopting drip irrigation decreases, causing a slight shift from drip irrigation toward flood irrigation. Additionally, because flood irrigation has been used for decades as the primary technique in the date industry, when the government withholds its financial support to new farms, they are more likely to adopt flood irrigation due to its initial level of diffusion among date farms. As a result, the effect of the cost ratio on the flood adoption rate rises higher and higher as the cost ratio increases. Contrarily, as the percentage of subsidy increases, the cost of drip irrigation becomes lower than that of flood irrigation; thus, the effect on the flood adoption rate falls lower over time.

Similar to Figure 25.a, the inflection point (0.5,1) represents the baseline scenario where the cost of the flood irrigation system is twice that of the drip irrigation system. In this case, the effect on the conversion rate to flood irrigation is 1. The graph falls between two extreme points, (0,0) and (2,2). The first extreme point presents a case where the cost of drip irrigation systems is entirely subsidized dropping the conversion rate of flood irrigation to zero. The other point demonstrates an inverse situation where the cost of drip irrigation is twice that of flood irrigation, encouraging farms to adopt flood irrigation systems through an increase in their conversion rate. The stock and flow diagram and equations are shown below in Figure 6-14 and Table 6-8, respectively. Data used to structure this module is drawn from (The General Authority for Statistics, 2018).

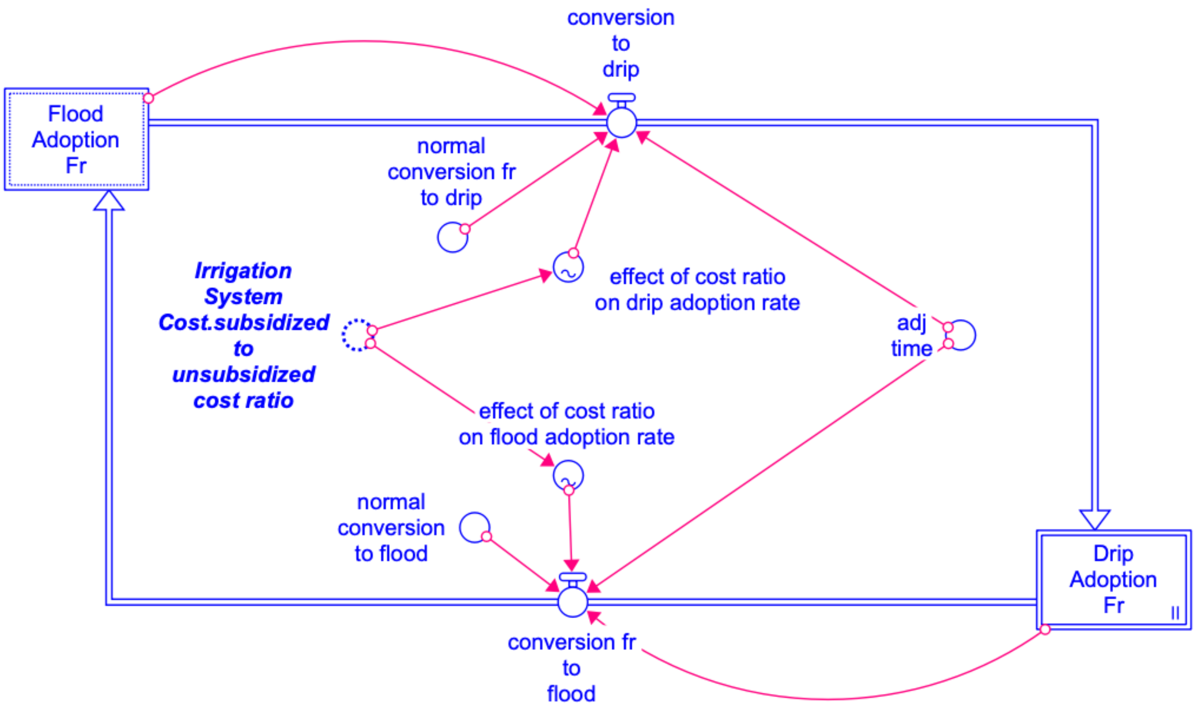


Figure 6-14: Stock and Flow diagram of the Irrigation Adoption Rates

Table 6-8: Irrigation Adoption Rates Module Equations

	Equation	Properties	Units
Irrigation Adoption Rates			
Drip Adoption Fr(t)	Drip –adoption Fr (t - dt) + (conversion to drip – conversion fr to flood) * dt	INIT Drip Adoption Fr = .50	Dimensionless
Flood Adoption Fr(t)	Flood –adoption Fr (t - dt) + (conversion fr to flood – conversion to drip) * dt	INIT Flood Adoption Fr = .50	Dimensionless
Conversion fr to flood	(Drip_Adoption_Fr*effect_of_cost_ratio_on_flood_adoption_rate*normal_conversion_to_flood*1/adj_time) +(Drip Adoption Fr*0/adj time)		1/year
Conversion to drip	(Flood_Adoption_Fr*effect_of_cost_ratio_on_drip_adoption_rate*normal_conversion_fr_to_drip*1/adj_time)+(Flood_Adoption_Fr*0/adj_time)		1/year
Adj time	1		year
Effect of cost ratio on drip adoption rate	GRAPH(Irrigation_System_Cost.subsidized_to_unsubsidized_cost_ratio) Points: (0.000, 2.000), (0.125, 1.944), (0.250,		Dimensionless

	1.810), (0.375, 1.4844), (0.500, 1.000), (0.625, 0.727), (0.750, 0.486), (0.875, 0.316), (1.000, 0.216), (1.125, 0.155), (1.250, 0.115), (1.375, 0.085), (1.500, 0.065), (1.625, 0.045), (1.750, 0.035), (1.875, 0.020), (2.000, 0.000)		
Effect of on flood adoption rate	GRAPH(Irrigation_System_Cost.subsidized_to_unsubsidized_cost_ratio) Points: (0.000, 0.000), (0.125, 0.078), (0.250, 0.262), (0.375, 0.582), (0.500, 1.000), (0.625, 1.293), (0.750, 1.494), (0.875, 1.644), (1.000, 1.749), (1.125, 1.820), (1.250, 1.870), (1.375, 1.905), (1.500, 1.935), (1.625, 1.950), (1.750, 1.965), (1.875, 1.980), (2.000, 2.000)		Dimensionless
Normal conversion fr to drip	0.05		Dimensionless
Normal conversion to flood	0.05		Dimensionless
Total adoption fr	Flood Adoption Fr+ Drip Adoption Fr		Donless

6.4.5 Irrigation System Cost Module

This module has a computational structure that accounts for the purchased resources used in the date cultivation process. In reference to the emergy literature, these resources represent all the purchased inputs and are chosen according to the emergy evaluation performed (Odum, 1988, 1996).

The Irrigation Adoption Rates module is directly linked to the Irrigation System Cost module, where a number of exogenous parameters are incorporated to compute the total cost of the services assessed to facilitate date production. The total cost of services is then added as a ghost variable to the sub-module of Labor and Services (L&S) Emergy within the Emergy of Cultivation module. Because the irrigation cost is presented per tree, the number of trees is added as a ghost variable from the Groundwater Consumption module and is specified for each irrigation system to give a more accurate estimate of the total cost.

The cost of flood irrigation systems is estimated with reference to historical data on date palm tree irrigation in Saudi Arabia (The National Center for Palms and Dates, 2018a). For drip irrigation, no data was found to estimate a realistic cost for implementing the drip system; consequently, this study assumes different price points for testing purposes. Overall, the module employs a computational structure bridging the dynamics of the preceding module, P1 Government Subsidy, with the subsequent module, Irrigation Adoption Rates. The module's structure and equations are presented below in Figure 6-15 and Table 6-9, respectively. The detailed emergy equations are presented in Section 5.1, number 12.

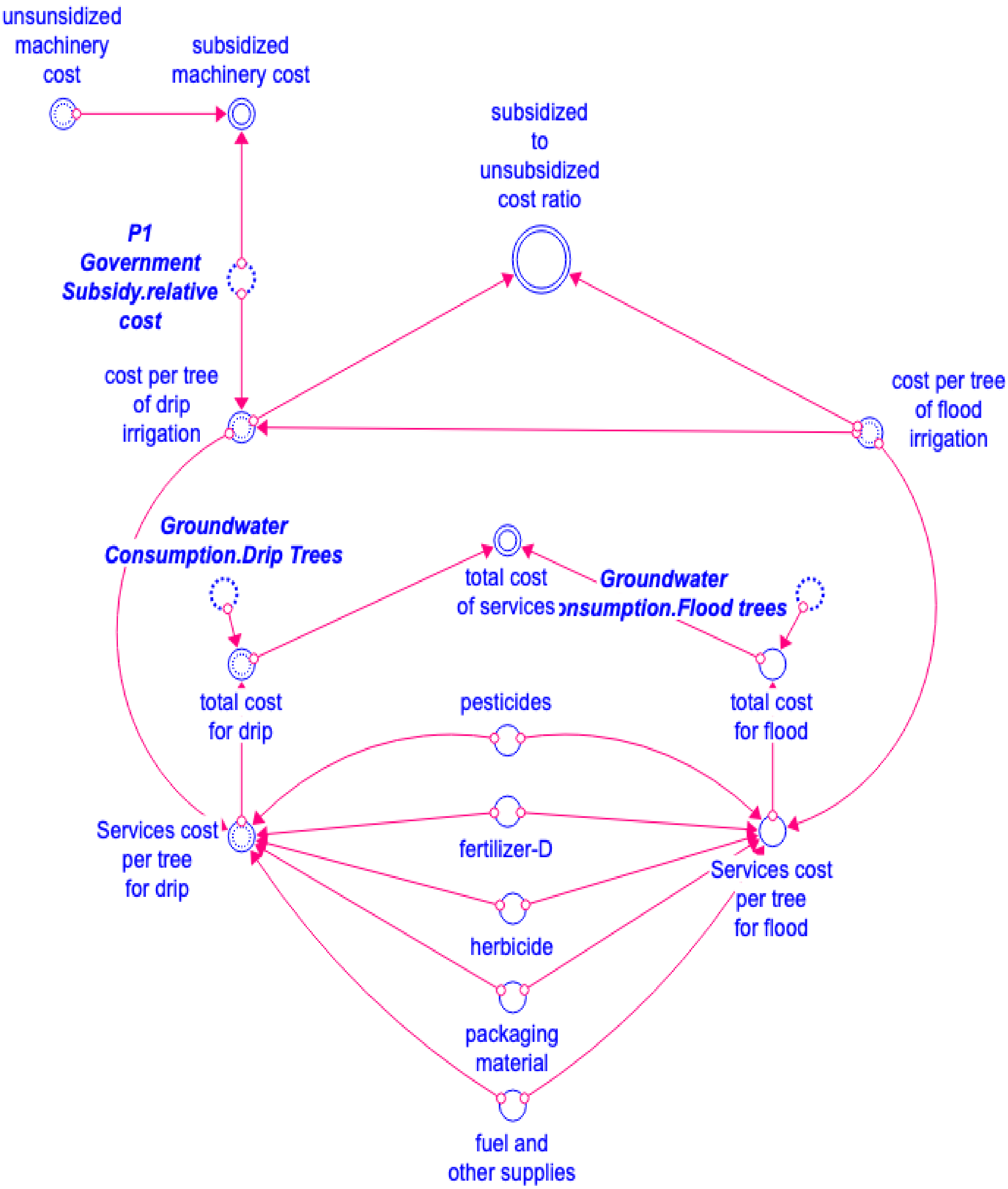


Figure 6-15: Stock and Flow Diagram of the Irrigation System Cost

Table 6-9: Irrigation System Cost Module Equations

	Equation	Units
Irrigation System Cost		
Cost per tree of drip irrigation	Cost per tree of flood irrigation-(cost per tree of flood irrigation*P1 Government Subsidy. Relative cost)	$/tree/year
Cost per tree of flood irrigation	.94	$/tree/year
"fertilizer-D"	8.28	$/tree/year
Fuel and other supplies	2.63	$/tree/year
herbicide	0.96	$/tree/year
Packaging material	3.59	$/tree/year
pesticides	1.73	$/tree/year
Services cost per tree for drip	fuel_and_other_supplies+packaging_material+pesticides +herbicide+"fertilizer-D"+cost_per_tree_of_drip_irrigation	$/tree/year
Services cost per tree for flood	pesticides+"fertilizer-D"+herbicide+packaging_material+fuel_and_other_supplies+cost_per_tree_of_flood_irrigation	$/tree/year
Subsidized machinery cost	unsunsidized_machinery_cost-(unsubsidized_machinery_cost*P1_Government_Subsidy.relative_cost)	$/year
Subsidized to unsubsidized cost ratio	cost_per_tree_of_drip_irrigation/cost_per_tree_of_flood_irrigation	Dimensionless
Total cost for drip	Services_cost_per_tree_for_drip*Groundwater_Consumption.Drip_Trees	$/year
Total cost for flood	Services_cost_per_tree_for_flood*Groundwater_Consumption.Flood_trees	$/year
Total cost of services	Total cost for drip + total cost for flood	$/year
Unsubsidized machinery cost	1404480	$/year

6.4.6 Government Subsidy Module P1

This module focuses on government incentives to promote the adoption of modern irrigation system technologies (i.e., drip irrigation). Under Royal Decree No. M/9 (2009), the Saudi government provides up to a 50% subsidy to facilitate the implementation of drip irrigation in an attempt to reduce groundwater consumption. These agricultural financial aids are offered in the form of a subsidy to reduce the cost of implementing modern drip irrigation systems (Agricultural Development Fund, 2019). For instance, farmers implementing drip irrigation systems enjoy a financial advantage by complying with the government's recent movements toward sustainable consumption of natural resources (Goals, 2018). The purpose is to explore the potential merits of adopting a dynamic approach by testing various levels of government subsidy based on emergy evaluations.

In this module, the percentage of non-renewable emergy (with L&S) (*%N*) is used as an indicator to measure the non-renewable contribution of natural local resources to the total emergy of the investigated system (including L&S). High and low percentages indicate more and less intensive exploitation of non-renewable resources, respectively. *%N* is normalized by its initial value without policy intervention to represent the underlying non-linear relationship between the two variables (Saeed and Irdatttidris, 1984) and to measure its effect on the subsidy through a graphical function named "effect of *%N* on subsidy."

The graphical function is an S-shaped curve with a negative slope. It demonstrates the relationship between *%N* and the subsidized cost percentage of the irrigation systems. The first extreme point (0,2) indicates that the system operates entirely using renewable resources, which corresponds to the highest effect on subsidy. Contrarily, the point (2,0) indicates that the system is entirely dependent on non-renewable resources, resulting in a withholding of the offered subsidy.

The inflection point (1,1) illustrates the current scenario, in which the government supports the date production industry with a 50% subsidy. With reference to the initial scenario, when *%N* is less than 1, it indicates that the system managed to reduce the consumption of non-renewable resources. In this case, the effect on the subsidy is higher, thus proportionally increasing the percentage of subsidized cost. When *%N* is larger than 1, it indicates that the system consumes more non-renewable resources than in the initial scenario. The effect on the subsidy is lower in this case, thus reducing the percentage of subsidized cost or the relative cost. Figures 6-16 and 6-17 below show the graphical function and module structure, respectively, and the equations are listed in Table 6-10.

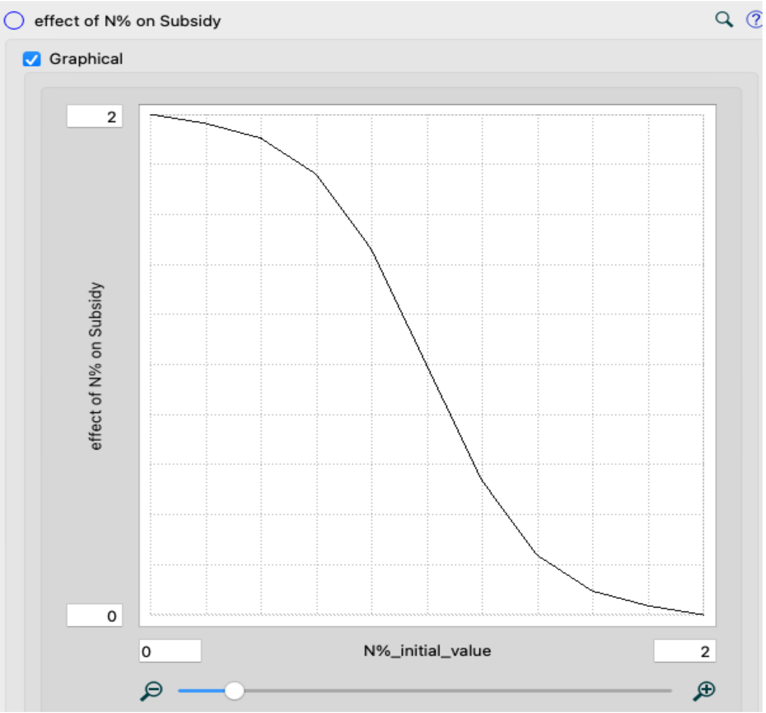


Figure 6-16: Effect of N% on Subsidy Graphical Function

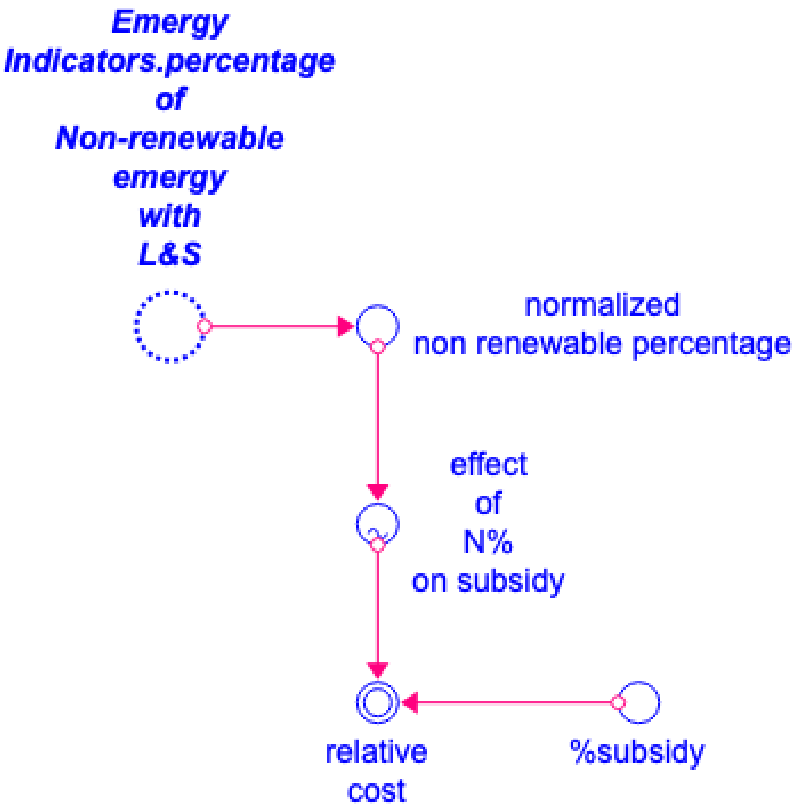


Figure 6-17: Stock and Flow Diagram of P1 Government Subsidy

Table 6-10: P1 Government Subsidy Module Equations

	Equation	Units
P1 Government Subsidy		
%subsidy	0.50	Dimensionless
Effect of N% on subsidy	GRAPH (normalized non-renewable percentage) Points: (0.000, 1.98661429815), (0.200, 1.96402758008), (0.400, 1.90514825364), (0.600, 1.76159415596), (0.800, 1.46211715726), (1.000, 1.000), (1.200, 0.53788284274), (1.400, 0.238405844044), (1.600, 0.0948517463551), (1.800, 0.0359724199242), (2.000, 0.0133857018486)	Dimensionless
Normalized non-renewable percentage	Emergy Indicators. Percentage of Non-renewable_emergy_with L&S/INIT(Emergy Indicators. Percentage of Non-renewable emergy with L&S)	Dimensionless
Relative cost	Effect of N% on subsidy*%subsidy	Dimensionless

6.4.7 Environmental Concerns Module P2

The second policy (P2) reflects the Saudi government's national strategy of increasing date production to achieve food self-sufficiency and increase date exports while preserving natural non-renewable resuources (e.g., groundwater) (MEWA, 2020; Ministry of Environment Water and Agriculture, 2018a; The General Authority for Statistics, 2020)

The second policy intervention implemented in this model is the effect of environmental concerns caused by date production. It aims to manage environmental concerns through the lens of EA by controlling the cultivated area used for date palms. For instance, if date production is excessively depleting groundwater resources, the government can impose some restrictions against expanding the cultivated area as a resource preservation measure. One such example of government actions to address environmental concerns is controlling the cultivated area of some crops, such as wheat and fodder in 2015, according to Royal Decree No. M/66 (2015).

This module incorporates another emergy indicator, emergy loading ratio (ELR), which measures the environmental pressure caused by the system's operations. ELR is normalized by its initial value without policy intervention to reflect the non-linear relationship between the two variables (Saeed and Irdatttidris, 1984) and to create a measuring index using a graphical function named "effect of ELR on area growth rate." The graphical function exhibits a logarithmic decay, suggesting that as ELR increases over time, the effect on growth rate diminishes. The first extreme point (2,0) suggests that when ELR is twice its initial value, environmental concerns increase sharply, forcing the effect on expanding the cultivated area to drop to zero in order to alleviate some of the growing environmental concerns. The second extreme point (0,1.5) indicates a case in which the value of ELR is reduced to zero, reflecting an optimistic scenario wherein no environmental concerns are raised regarding date production. It is in this situation that the effect of increasing the growth rate of the cultivated area is the highest. The inflection point (1,1) mirrors the current ELR under existing agricultural expansion strategies. Below are the graphical function, structure, and equations of the P2 Environmental Concerns module in Figures 6-18 and 6-19 and Table 6-11, respectively.

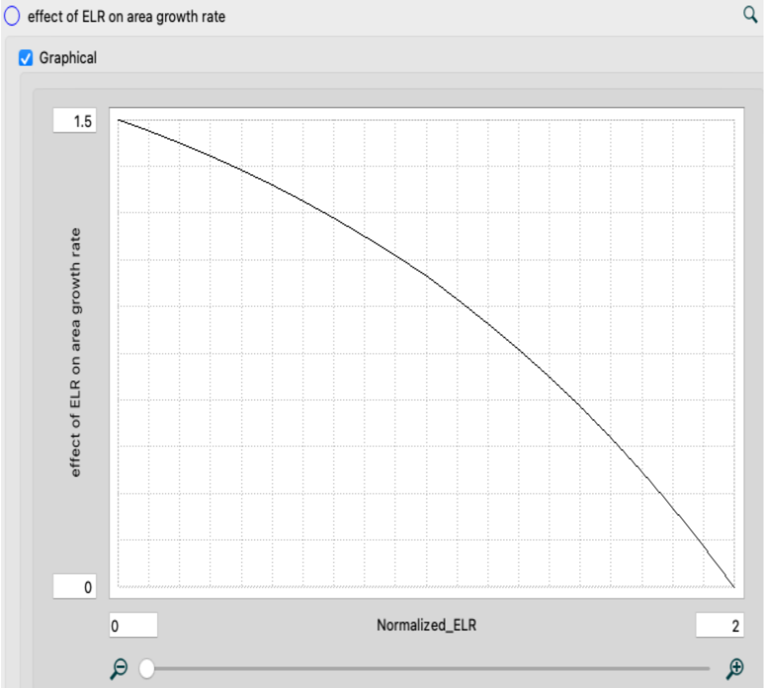


Figure 6-18: Effect of ELR on Area Growth Rate Graphical Function

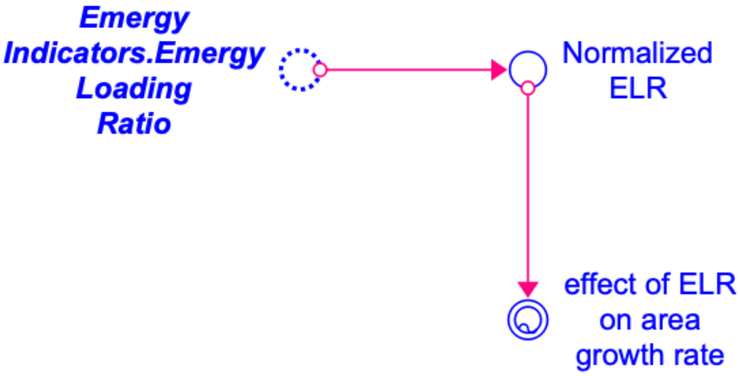


Figure 6-19: Environmental Concerns Module

Table 6-11: P2 Environmental Concerns Module Equations

	Equation	Units
P2 Environmental Concerns		
Effect of ELR on area growth rate	GRAPH(Normalized ELR) Points: (0.000, 1.500), (0.100, 1.46367271508), (0.200, 1.42474099332), (0.300, 1.38302422732), (0.400, 1.33832956606), (0.500, 1.29044834666), (0.600, 1.23914560182), (0.700, 1.18418692097), (0.800, 1.12553423268), (0.900, 1.06370573283), (1.000, 1.000), (1.100, 0.924191737932), (1.200, 0.845882472524), (1.300, 0.763147425356), (1.400, 0.674837333705), (1.500, 0.58035188161), (1.600, 0.479277294089), (1.700, 0.371188044827), (1.800, 0.255617444686), (1.900, 0.132065535117), (2.000, 0.000)	Dimensionless
Normalized ELR	Emergy Indicators.Emergy Loading Ratio/INIT (Emergy Indicators.Emergy Loading Ratio)	Dimensionless

6.4.8 Cultivated Area Module

The Cultivated Area module represents the aggregate area of date-bearing palm trees, which is estimated at 117,881 hectares (The General Authority for Statistics, 2020). The dynamic of the module is illustrated by a stock representing the accumulated cultivated area that increases according to the annual area increase rate and decreases according to a decrease rate. The inflow and outflow are affected by a normal rate that is estimated using historical data. Data published by the Food and Agriculture Organization of the United (2022) was used to determine the average growth rate of cultivated area under date palm trees, taking the last five years as a reference period. Table 6-12 below shows the growth pattern in the cultivated area of date palm trees.

Table 6-12: Palm Tree Cultivated Area from 2015-2020

Year	**Unit**	**Value**	**%Change**
2015	ha	109427	2.0
2016	ha	111615	2.0

2017	ha	113848	2.0
2018	ha	116125	2.0
2019	ha	136992	17.9
2020	ha	152705	11.5

Based on the data published during the period 2015–2020, the average growth rate in the cultivated area of date palm trees is approximately 6%. Thus, the normal growth rate is estimated at 6%. Due to the lack of data regarding the reduction rate in the cultivated area under date palm trees, the normal reduction rate is set at 6% for modeling reasons only.

The dynamic of the cultivated area changes in response to changes in the ELR, which is transformed into a measurable index by using the ELR effect on the area growth rate graphical function. For instance, with reference to the initial value of ELR, when its value increases, the effect on the area growth rate decreases, causing the cultivated area to decline—and vice versa. The relative growth rate converter represents the growth rate when P2 is implemented. The P2 policy impacts the cultivated area via the "effect of ELR on area growth rate" graphical function as it fluctuates based on the system's environmental performance. The module's stock and flow diagrams, as well as the equation table, are shown in Figure 6-20 and Table 6-13, respectively.

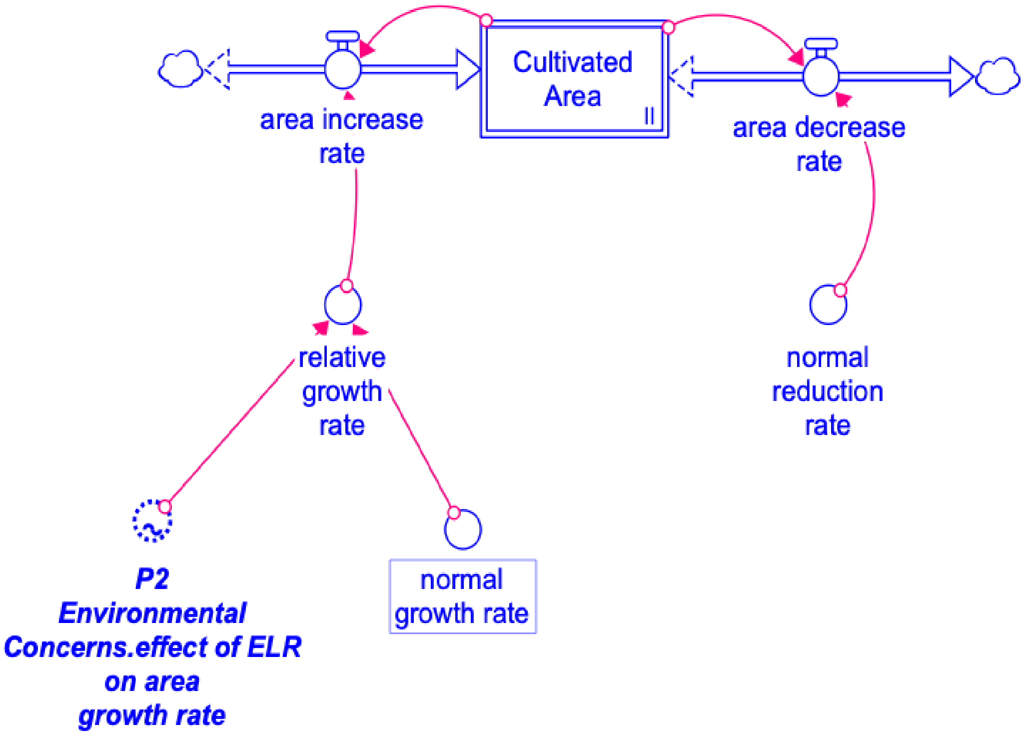


Figure 6-20: Stock and Flow Diagram of the Cultivated Area

Table 6-13: Cultivated Area Module Equations

	Equation	Properties	Units
Cultivated Area:			
Cultivated Area(t)	Cultivated Area(t - dt) + (area increase rate – area decrease rate) * dt	INIT Cultivated Area = 117881	Hectare
Area decrease rate	Cultivated Area*normal reduction rate		Hectare/year
Area increase rate	Cultivated Area*relative growth rate		Hectares/year
Normal growth rate	0.06		1/year
Normal reduction rate	0.06		1/year
Relative growth rate	Normal growth rate*P2 Environmental Concerns. Effect of ELR on area growth rate		1/year

6.5 Testing and Validating

This section describes the testing and validation procedures that are necessary to establish confidence in the constructed emergy SD model (Forrester, 1973). Namely, these are: 1) the unit check test, 2) extreme condition testing, and 3) sensitivity analysis (Sterman, 2000). These three validity tests were selected due to the nature of the presented model and its limitations deriving from the scarcity of relevant literature.

6.5.1 Unit Check test

The investigated system comprises the upstream activities taking place within the supply chain under study, which include date cultivation as the source of the by-product (date seeds) being evaluated. The model is structured with a set of multidimensional variables that have been checked automatically using Stella Architect. The unit check indicates that the variables are consistent with the generic SD structure.

6.5.2 Extreme Condition Testing

Extreme condition testing is conducted to test the model's validity. An interface is created using Stella Architect to present the model's behavior under each extreme condition test.

Test 1: Zero Area Growth Rate

The first extreme condition test involves a complete reduction of the cultivated area by dropping the area increase rate to 0, regardless of the irrigation adoption rate for the two systems under investigation. Such extreme interventions can be imposed as mitigation measures to deal with cases such as droughts, accelerated erosion, or over-exploitation of non-renewable resources.

This test simulates a historical event that occurred in 2015, when the Saudi Arabian government issued a royal decree suspending wheat and fodder production as part of a water preservation policy (Ministry of Environment Water and Agriculture, 2018a; Royal Decree No. M/66, 2015). The model is simulated under a zero-growth rate in the cultivated area, and the results are demonstrated in Figure 6-21.

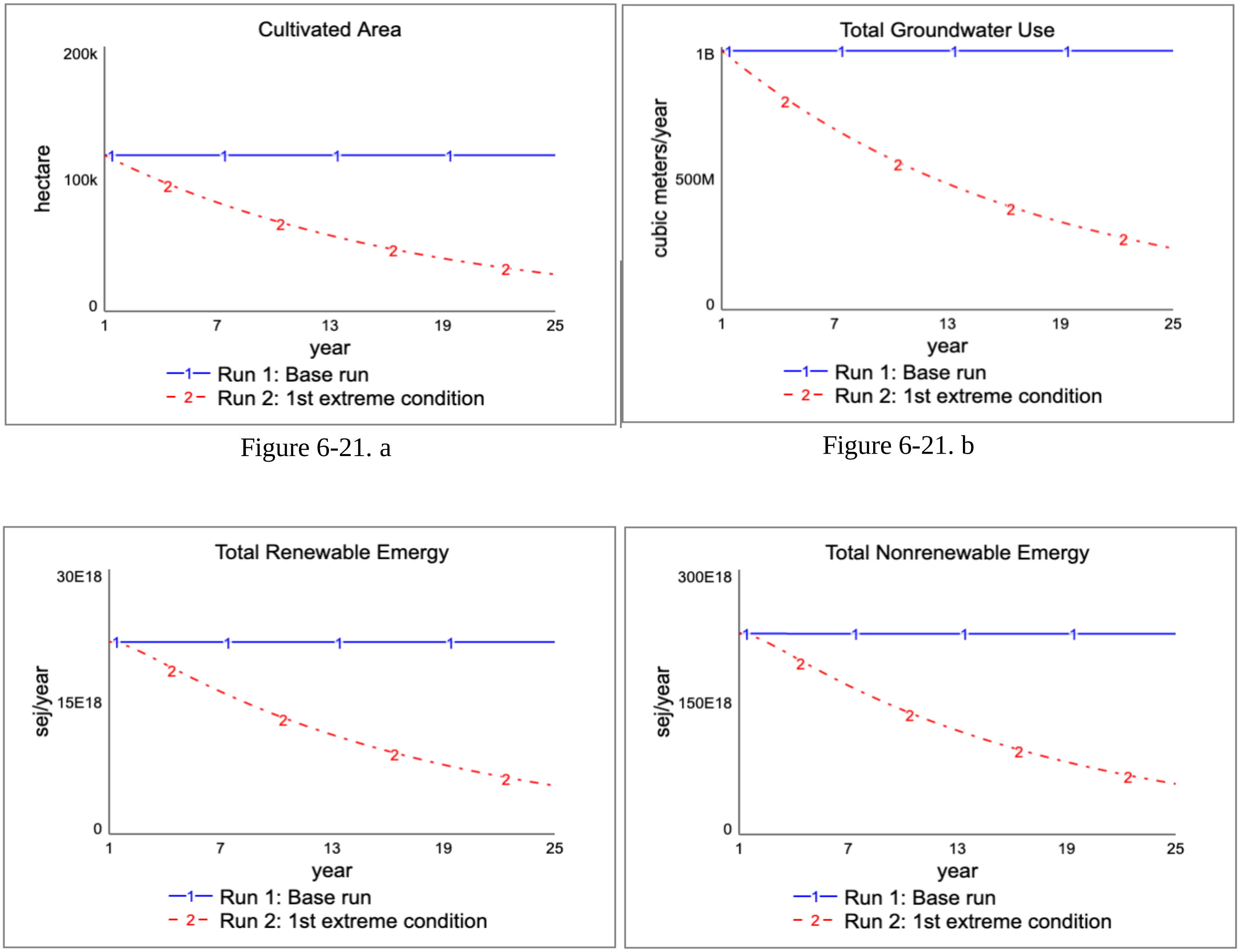


Figure 6-21. a

Figure 6-21. b

Figure 6-21. c

Figure 6-21. d

Figure 6-21: Simulation Runs of the First Extreme Condition Test of Zero Area Increase Rate

Figure 6-21.a shows two simulation runs of the cultivated area. The first run shows the model’s behavior under a steady-state condition. The second run is the tested scenario of an extreme condition wherein the normal growth rate is reduced to zero, as opposed to the normal annual increase rate of 6%. The model behaves as expected, showing an exponential decline in the cultivated area over time. Following the decline in cultivated area, the number of date palm trees is also expected to decline in response to the reduction in area per tree. As expected, the consumption of groundwater follows the decline in the number of date palm trees, as shown in Figure 6-21.b. In response to the decline in the consumption of groundwater, the energy and emergy of groundwater also decline, causing a reduction in total renewable (Figure 6-21.c) and non-renewable emergy (Figure 6-21.d). Overall, the model behaved sensibly to changes in the cultivated area.

Test 2: 100% Flood Adoption Rate.

The second extreme condition test investigates the model’s behavior under a 100% adoption of flood irrigation. To some extent, this scenario resembles a true historical period during which flood irrigation dominated the farmed area in Saudi Arabia with an adoption rate as high as 70% (Al-Shayaa, 2011). To simulate the second extreme condition test, the normal conversion fraction to flood is increased to 100%. The generated behavior is expected to reflect an increase in groundwater consumption with a compounding effect on both the energy and emergy values of the overall system. Moreover, the emergy indicators are expected to increase as a result of the increase in groundwater consumption.

The results of the simulated scenario are illustrated below in Figures 6-22.a–6.22f, which show that the model is simulated at a 100% conversion rate from drip to flood irrigation systems, meaning that flood irrigation predominates throughout the entire cultivated area. The results of the simulation indicate that the model generated the expected behavior.

In response to the increase in the area under flood irrigation (Figure 6-22.a), the amount of groundwater consumed per hectare increases (Figure 6-22.d), as shown in Figure 34.c. This increase created a ripple effect on the emergy of non-renewable resources, ELR (Figure 6-22.f), and *%N* (Figure 6-22.f). The use of flood irrigation increased the emergy of non-renewable resources, which increased the environmental pressure of the system, as reflected by the increased ELR. Another expected output is the increase in *%N* (Figure 6-22.f) due to the increased consumption of non-renewable resources.

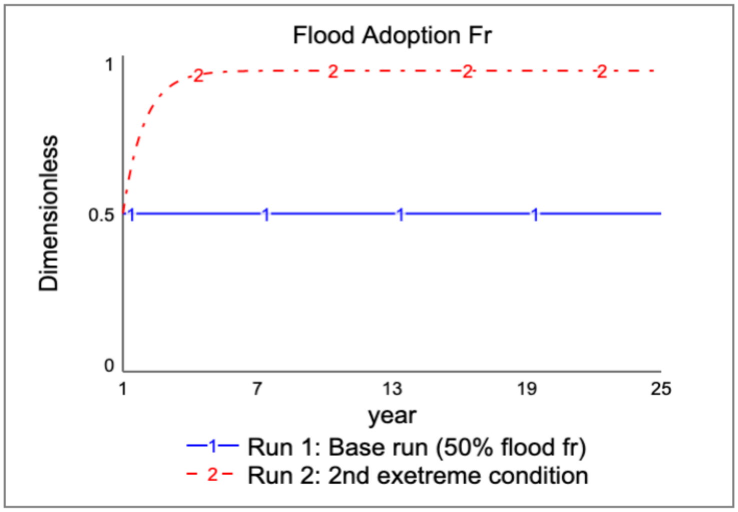


Figure 6-22. a

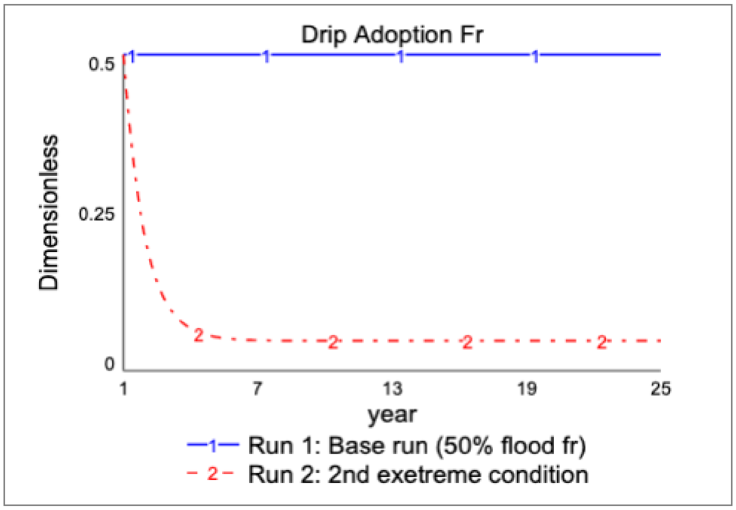


Figure 6-22. b

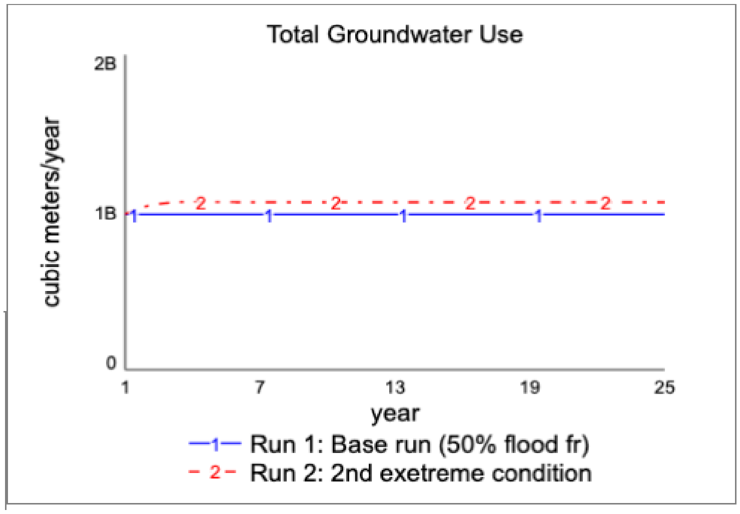


Figure 6-22. c

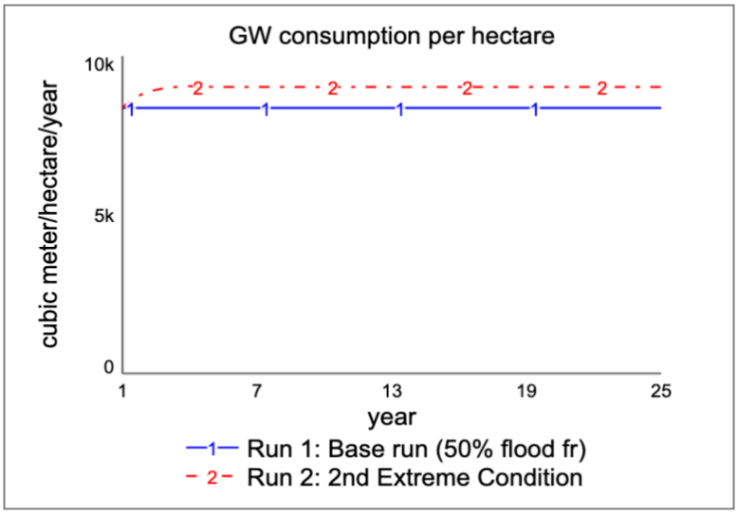


Figure 6-22. d

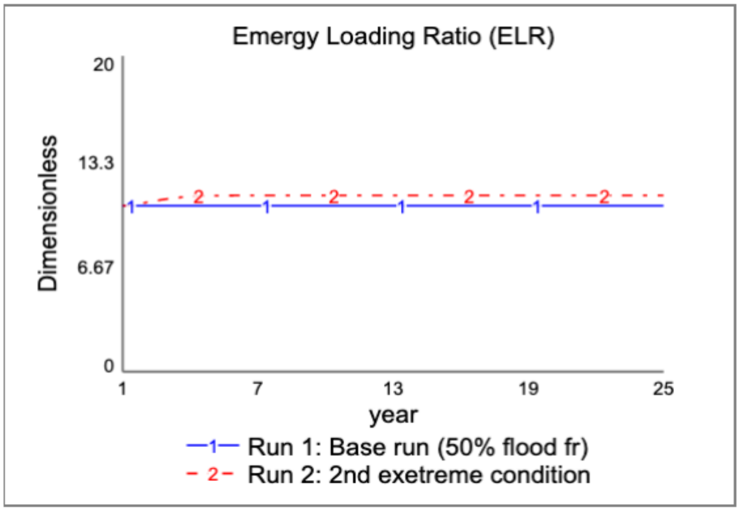


Figure 6-22. e

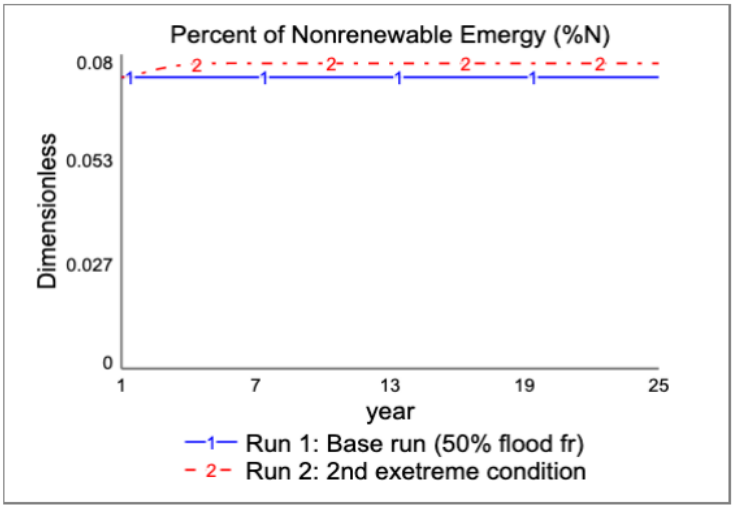


Figure 6-22. f

Figure 6-22: Simulation Runs of the Second Extreme Condition Test of 100% Flood Adoption Rate

Test3: Reducing the Annual Recharge Volume to Zero.

The third extreme condition reflects the impact of a severe water shortage on the emergy of the date cultivation system. This test mirrors one of the NRDT's essential elements—the impact of the natural system on organizational and supply chain performance—assuming that the severe water shortage is induced by direct natural forces. Data published by the Ministry of Environment Water and Agriculture (2018b) evaluates the current state of water consumption, indicating that at the current consumption rate within the agricultural sector, Saudi Arabia is suffering from a low recharge rate of non-renewable groundwater. Thus, this test represents an extreme condition of over-exploitation of non-renewable water sources in Saudi Arabia.

The model generates an expected behavior under an extreme condition of water scarcity. The groundwater reservoir declines exponentially, causing the storage to decline proportionally, as illustrated in Figure 6-23.a. As a result of this water shortage, the amount of groundwater used in irrigation (Total GW Use) declines slightly in response to the reduction in the groundwater availability factor (Figure 6-23.b). Despite the reservoir's groundwater shortage, however, the decline in Total GW Use is very slow because the storage remains sufficient to supply demand for irrigation water to the date palm industry.

With this reduction in the volume of groundwater used, the energy and emergy of groundwater are also reduced over time, as is the total emergy of non-renewable resources. This affects the values of the emergy indicators used in this evaluation. For instance, the %N and ELR declined over time (Figures 6-23.e and 6-23.f, respectively). To reflect the model's behavior under an extreme water shortage, an interface was created in Stella Architect. The figures below illustrate the result of the extreme condition under testing. Each figure shows two simulation runs, wherein Run 1 represents the baseline scenario in a steady-state situation and Run 2 illustrates the tested extreme condition of zero annual recharge volume. The results of testing an extreme condition of water scarcity revealed that the model generated the expected behavior.

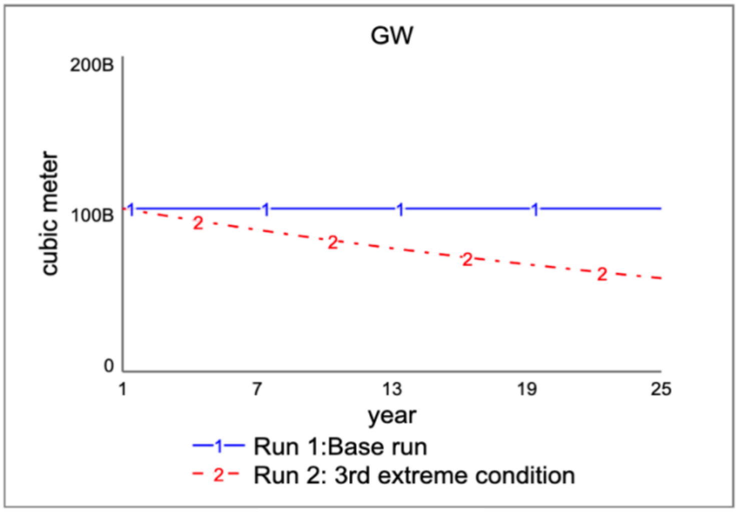


Figure 6-23. a

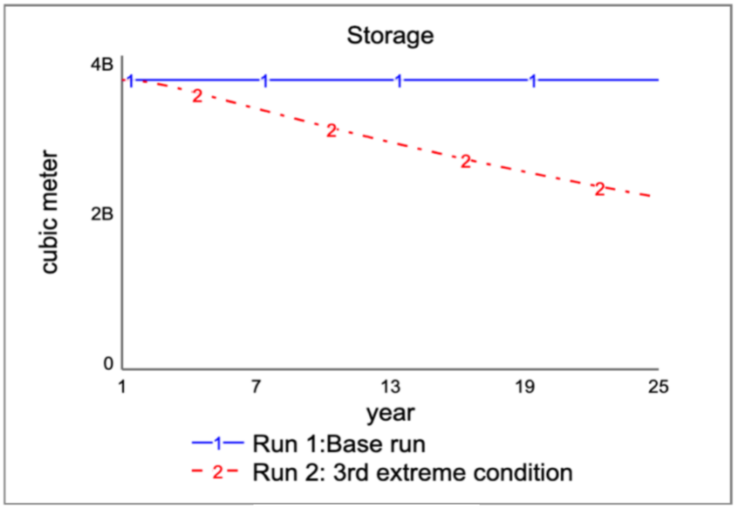


Figure 6-23. b

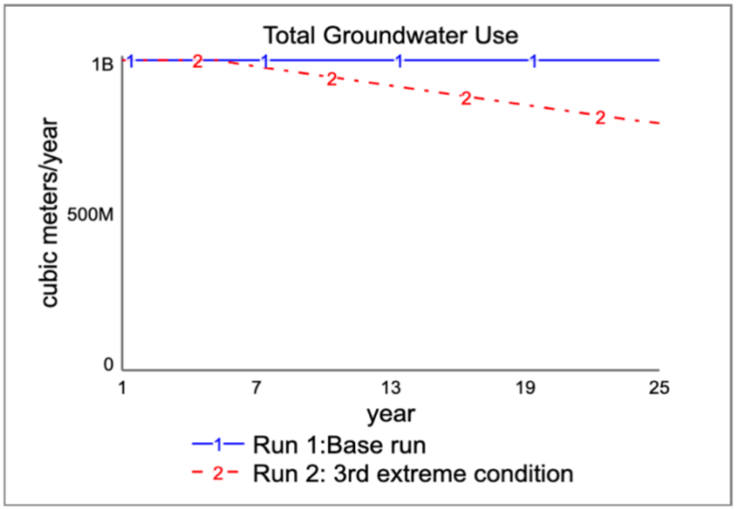


Figure 6-23. c

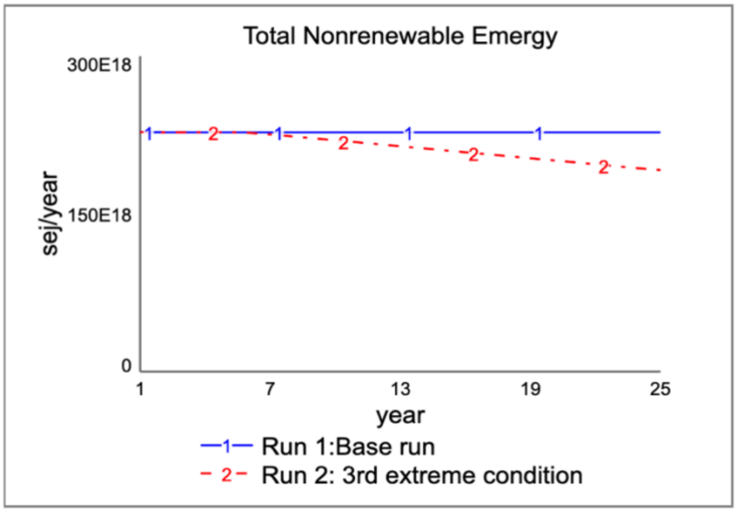


Figure 6-23. d

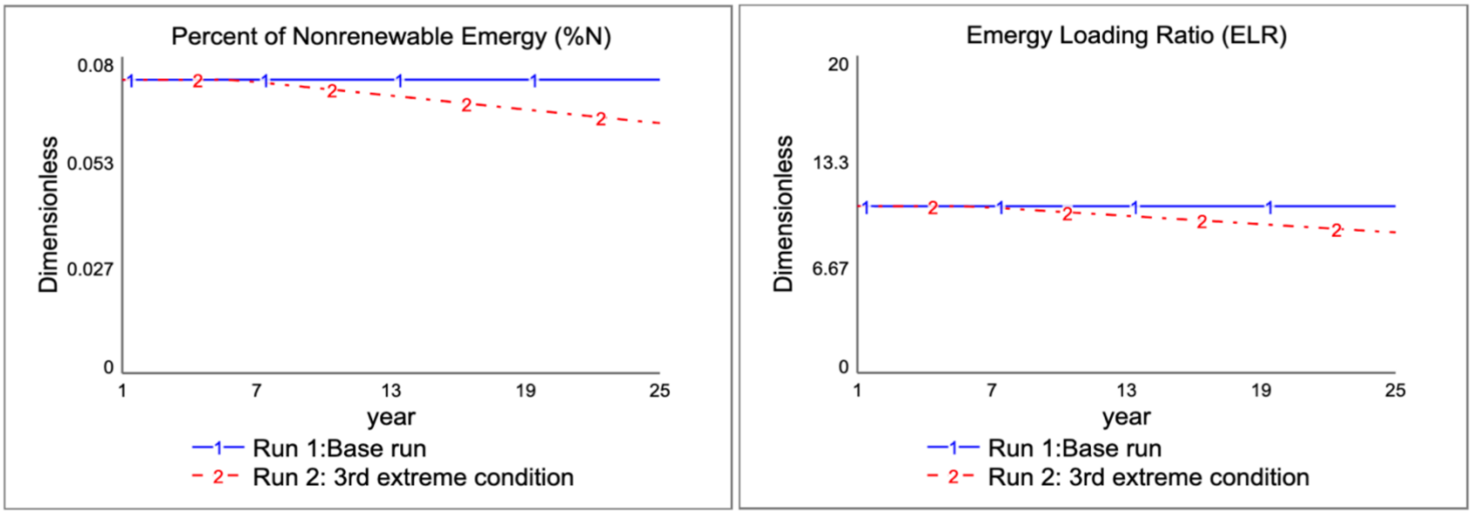


Figure 6-23. e

Figure 6-23. f

Figure 6-23:Simulation Runs of the Third Extreme Condition Test of Zero Annual Recharge Volume

Test 4: Testing the Effect of High Consumption Rate

A higher groundwater storage consumption rate would increase the volume of groundwater consumed (as long as the increase is within a normal range), allowing the stocks of groundwater and storage to replenish. The third extreme test is conducted to investigate the effect of a high storage consumption rate that exceeds its replenishment rate; to some extent, this represents a real challenge facing the agriculture industry in Saudi Arabia (Napoli et al., 2018). This extreme condition highlights the role of organizational and supply chain impact on the natural system investigating the element of the NRDT. According to the Ministry of Environment Water and Agriculture (2018b), the consumption rate of non-renewable water resources (e.g., groundwater) in Saudi Arabia is increasing by 7% annually. If no regulatory actions are taken to control the ever-increasing consumption of groundwater in the agricultural sector, Saudi Arabia will face an extreme water shortage crisis by the year 2050 (Rahman et al., 2022). Therefore, this extreme condition test mimics the situation of a high consumption rate, assessing the impact of such a condition on the emergy evaluation of date cultivation over time.

In a steady state, the initial normal groundwater consumption rate was estimated at 0.65, to run this extreme condition test the normal consumption rate is increased to 3 per year. The results show that the increased consumption significantly diminished the stock of groundwater (Figure 6-24.a) and storage (Figure 6-24.b). Furthermore, as expected, as the gap between the volume of groundwater consumed and groundwater storage shrinks over time, the fraction of groundwater used increases, and Total GW Use declines as the GW availability factor decreases (see Figures 6-24.c and 6-24.d). The structure of the Groundwater Consumption module controls the increase in the volume of Total GW Use within a certain rate of storage capacity.

As a result of the decline in Total GW Use, the model experienced a reduction in the energy and emergy values of groundwater as a non-renewable resource. Moreover, the emergy indicators ELR and *%N* decline in response to these changes, as shown in Figures 6-24.e and 6-24.g, respectively. Finally, the model behaved sensibly to the dramatic increase in the normal consumption rate. The results of this extreme test are shown below; each figure depicts two simulation runs, where Run 1 represents the baseline scenario in a steady-state situation and Run 2 illustrates the tested extreme condition of an increased normal consumption rate from 0.65 per year to 3 per year.

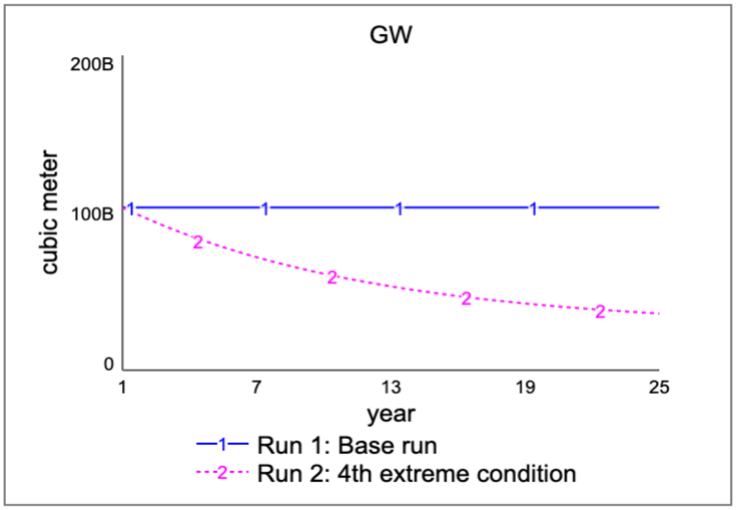


Figure 6-24. a

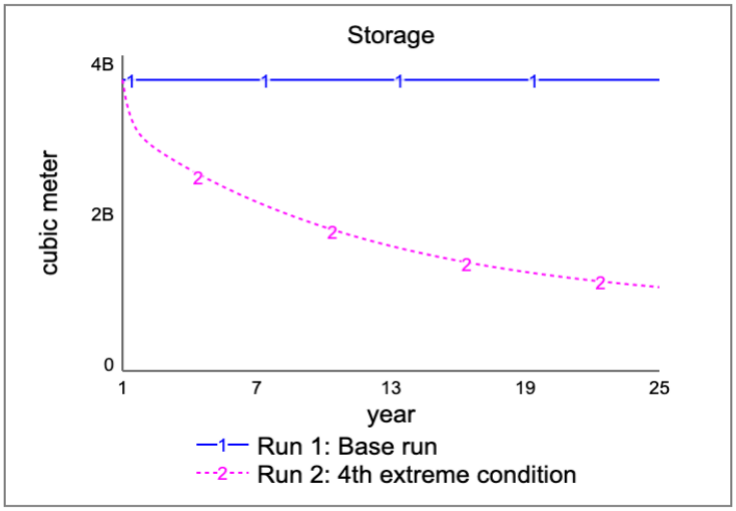


Figure 6-24. b

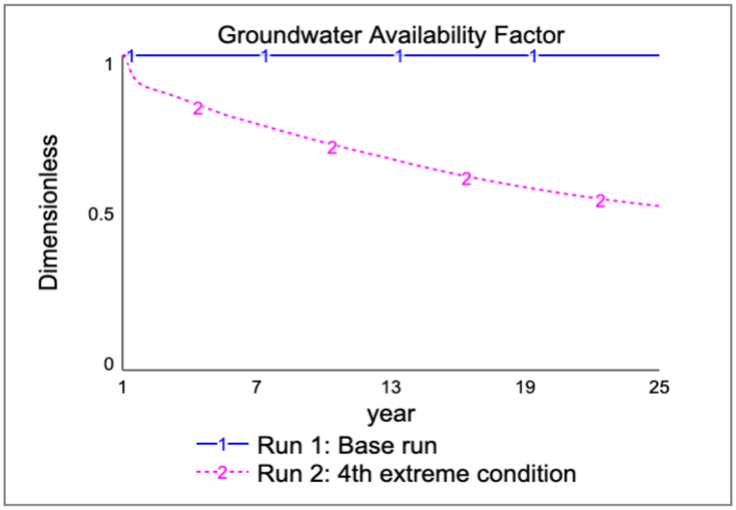


Figure 6-24. c

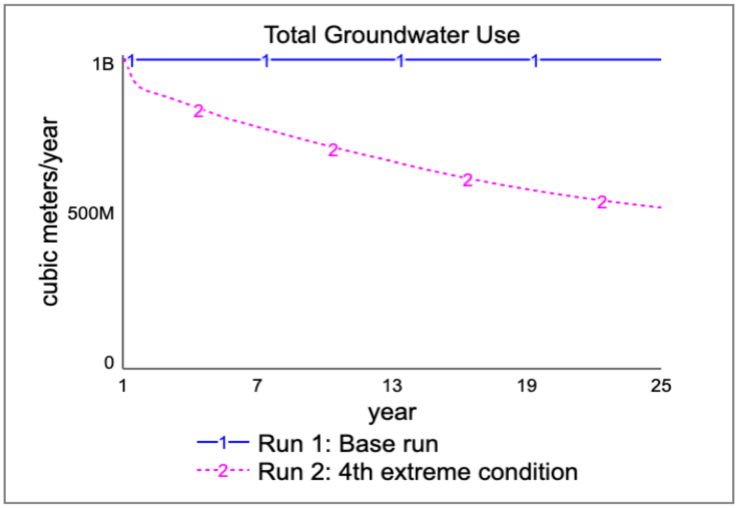


Figure 6-24. d

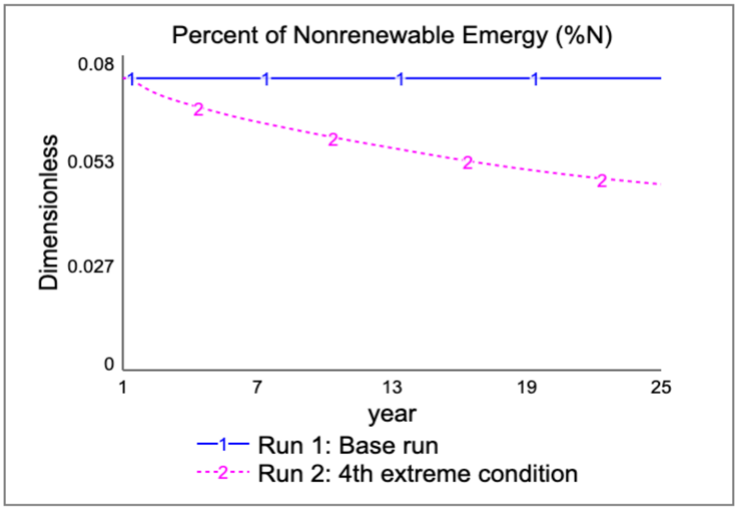


Figure 6-24. e

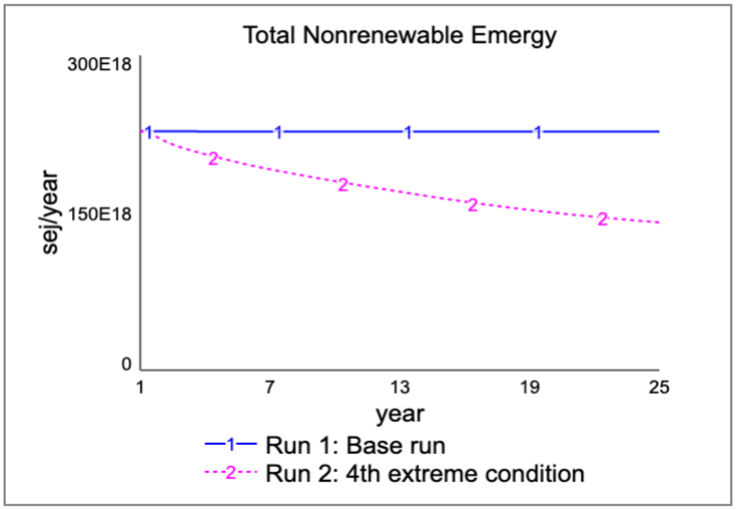


Figure 6-24. f

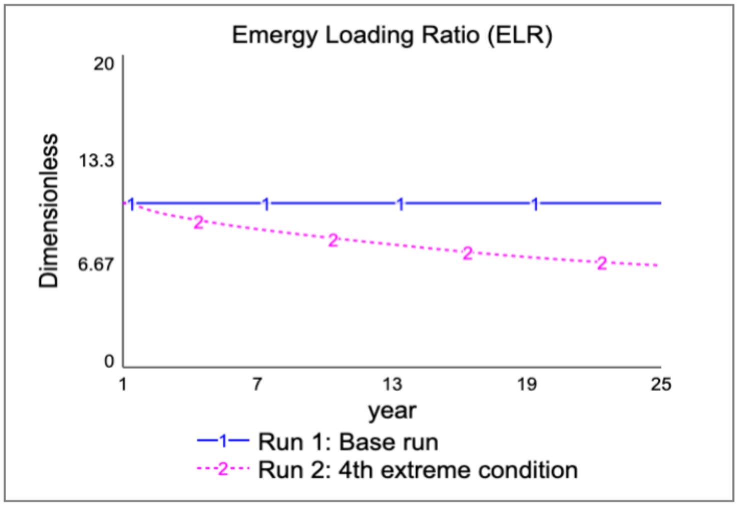


Figure 6-24. g

Figure 6-24: Simulation Runs of the Fourth Extreme Condition Test of an Increased Groundwater Normal Consumption Rate

Test 5: Increase in the Consumption Per Tree.

Another round of extreme testing is conducted to assess the model's behavior under an increase in the groundwater consumption per tree for each irrigation system. The main difference between this fifth extreme condition and the fourth extreme condition is that the fourth extreme condition tests the impact of a severe shortage in the main source of water dedicated to agricultural use. On the other hand, the fifth extreme condition tests the effect of increasing groundwater consumption. In this test, the amount of groundwater consumed annual per tree is doubled to 69.4 m^3/tree/year and 84 m^3/tree/year for the drip and flood irrigation systems, respectively.

After normalizing the effect of policy interventions (P1 and P2), the increase in consumption per tree led to an overall increase in total groundwater use (Figure 6-25.a), groundwater energy, groundwater emergy (Figure 6-25.c), *%N* (Figure 6-25.e), and ELR (Figure

6-25.f). The volume of groundwater consumed increased from 986E+06 m^3/year to 1.65E+09 m^3/year with a rapid drop during the first three years caused by the decline in the groundwater availability factor as the system withdraws more groundwater from storage. Overall, the model's behavior changed sensibly to the increase in the annual groundwater consumption per tree. The generated behavior is illustrated in the figures below, which show the baseline scenario (Run 1) and the tested extreme condition (Run 2).

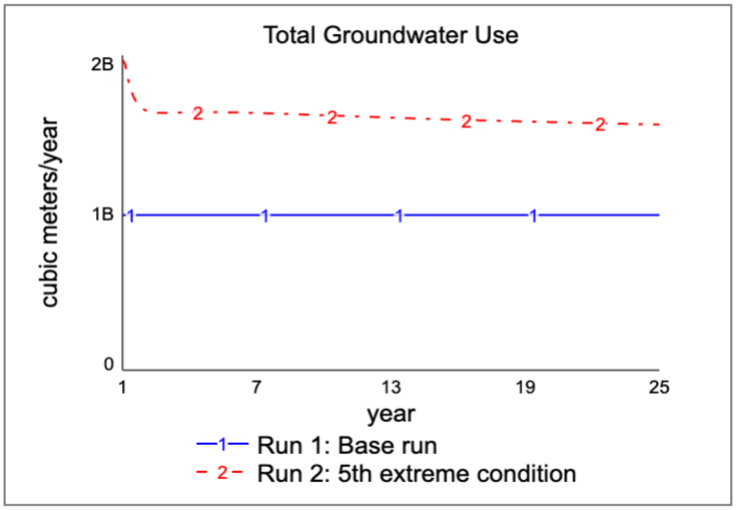


Figure 6-25. a

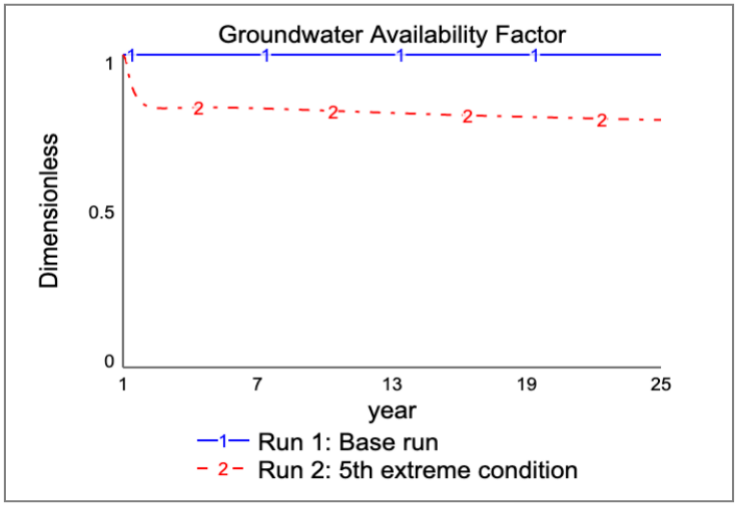


Figure 6-25. b

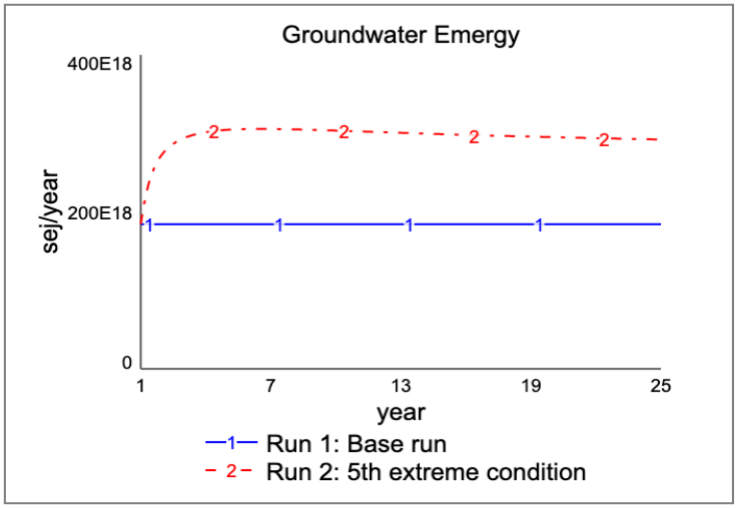


Figure 6-25. c

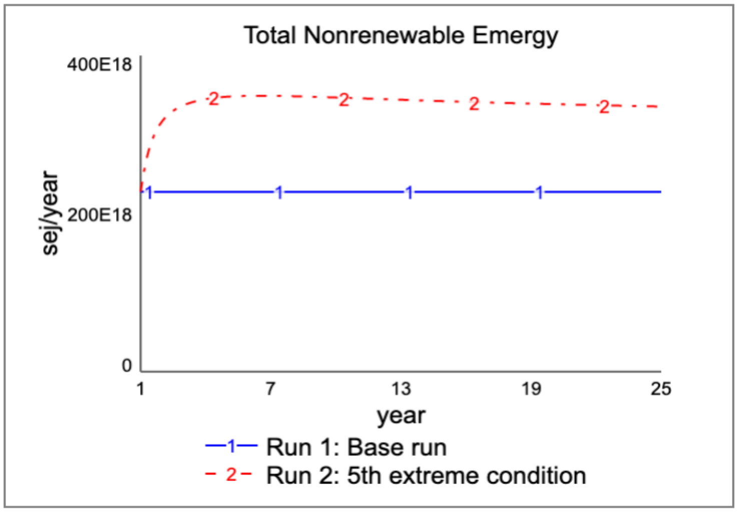


Figure 6-25. d

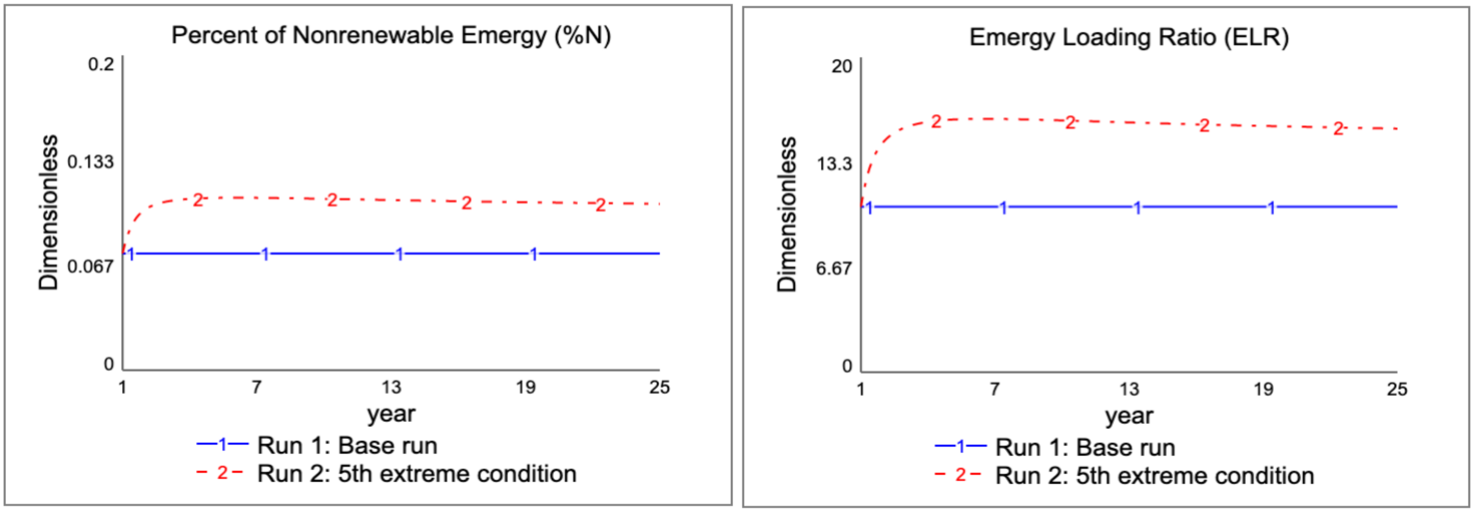


Figure 6-25. e

Figure 6-25. f

Figure 6-25: Simulation Runs of the Fifth Extreme Condition Test of an Increased in the Groundwater Consumption Per Tree

6.5.3 Sensitivity Analysis

Sensitivity Test 1

Multiple sensitivity analysis tests are performed to gain a deeper understanding of the constructed SD model. Without policy interventions, the first set of sensitivity analysis tests aim to determine the model's responsiveness to changes in the normal growth rate of the cultivated area, which is divided equally between drip and flood irrigation systems. In a steady state, the current growth rate of the cultivated area averages 6% annually (as mentioned in Section 6-12) for a cultivated area of approximately 118,000 hectares. The normal growth rate is simulated across three runs, beginning with 6% as the baseline, then doubling to 12%, and finally halving the baseline rate to 3%.

With an increased normal growth rate, the simulation results indicate that the model's sensitivity varies depending on the direction of change. For instance, the model is highly sensitive to the increase in the normal growth rate. As the growth rate is doubled to 12%, the cultivated area increases exponentially (Figure 6-26.a), leading to growth in total groundwater use (Figure 6-26.b), groundwater energy, groundwater emergy, non-renewable emergy (Figure 6-26.c), and renewable emergy (Figure 6-30.d).

As for the effect on the emergy indictors, ELR and *%N*, the doubled growth rate generated an interesting behavior. Although the increase in growth rate resulted in an increase in the cultivated area (and therefore in the use of groundwater), *%N* and ELR behaviors declined, as shown in Figures 6-26.e and 6-26.f, respectively. This occurs because the amount of groundwater consumption per hectare decreases as the area increases, thus alleviating some of the environmental pressure caused by excessive consumption. For the ELR, while both the numerator (the sum of the emergy of non-renewable resources and purchased resources) and the denominator (emergy of renewable resources) experienced an increase, the percent change in the denominator was higher (a 297% increase), whereas the numerator increased by 131%. Similarly, the percent increase in total L&S emergy (*U*) rose 284% for the *%N*. The effect of a doubled growth rate is illustrated in the figures below, with Run 1 as the baseline and Run 2 as the tested growth rate. Meanwhile, reducing the normal growth rate to 3% caused a decline in the cultivated area, total groundwater use, groundwater energy, groundwater emergy, non-renewable emergy, and renewable emergy.

The two emergy indicators, ELR and *%N*, were less sensitive to the decline in the normal growth rate. Moreover, while the halved growth rate led to a gradual decline in the cultivated area, the emergy indicators show an inconsequential increase: ELR increases slightly, from 10.5 to 10.6, while *%N* remains the same at around 7.4%. Similar to the results of the first sensitivity analysis test, here the discrepancy in the percent change between the numerator and denominator of each indicator caused them to change in a rather unexpected direction. For instance, in ELR, the denominator dropped by 0.2% more than the numerator, causing the ratio to increase marginally. However, for *%N*, the percent declines of the numerator and the denominator were both the same; thus, the contribution of non-renewable resources remains at the same level. Overall, halving the normal growth rate had no significant impact on the model's behavior. The results of the decline in growth rate are illustrated in the figures below, with Run 1 as the baseline and Run 3 as the tested growth rate of 3%.

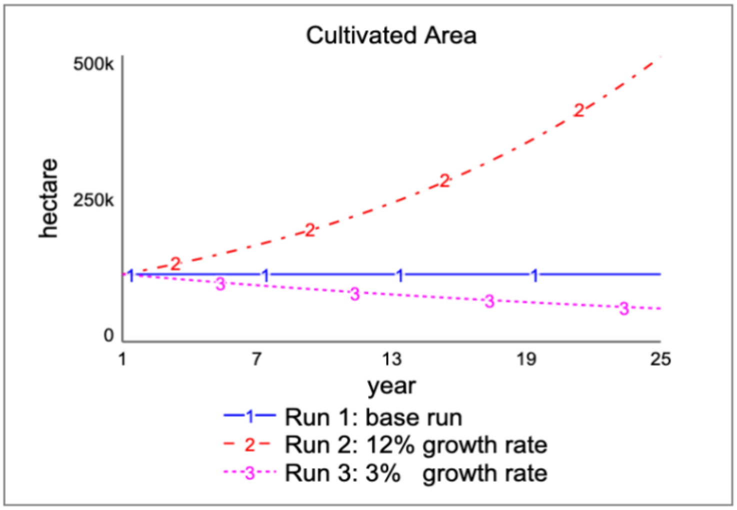


Figure 6-26.a

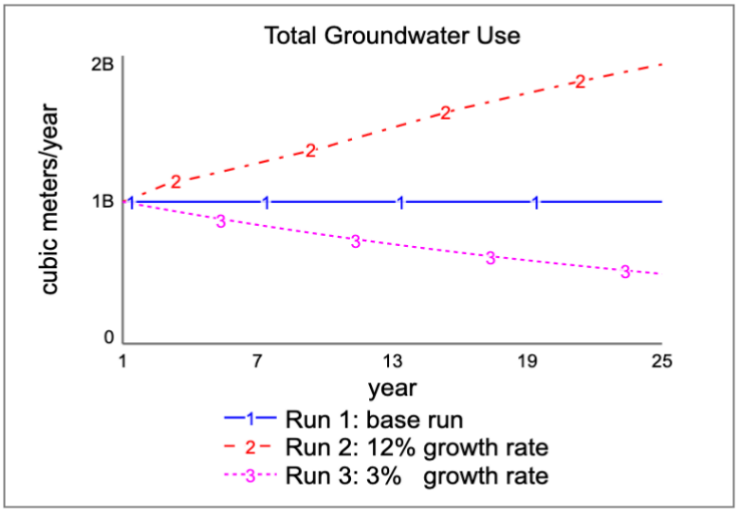


Figure 6-26.b

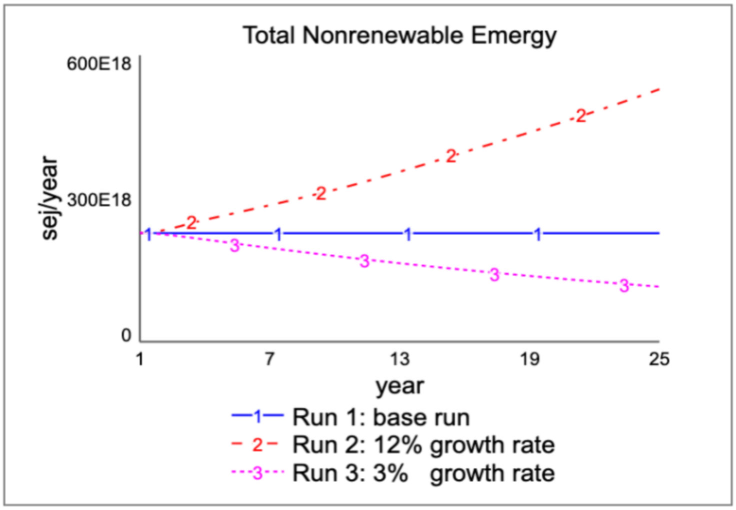


Figure 6-26.c

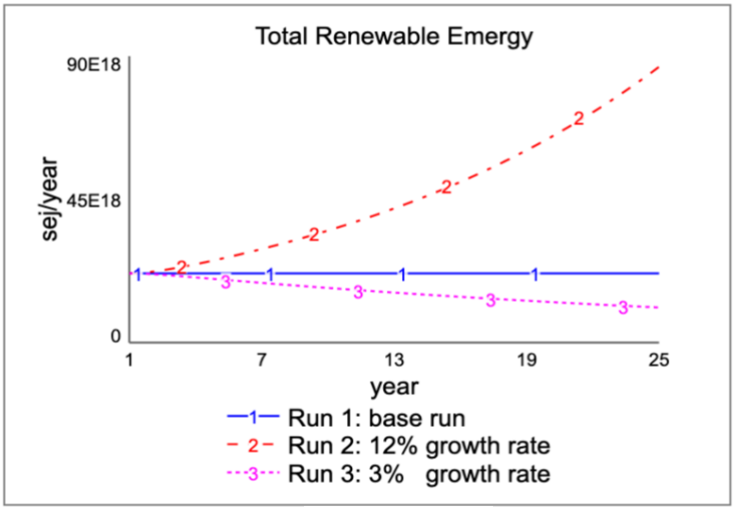


Figure 6-26.d

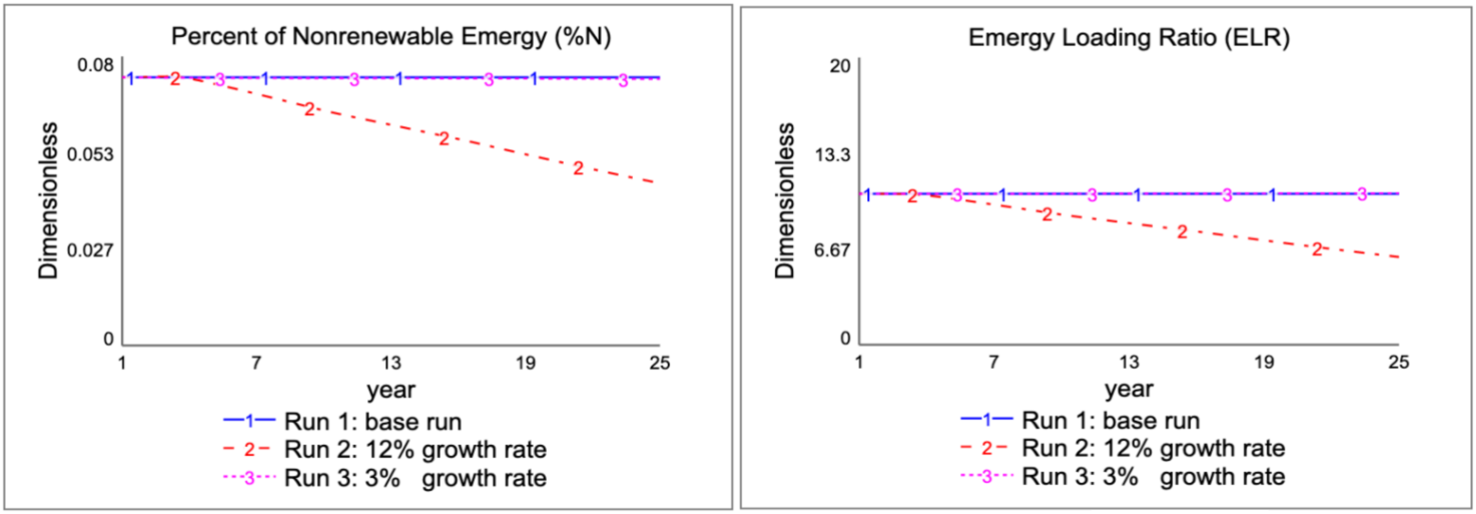


Figure 6-26.e

Figure 6-26.f

Figure 6-26: Sensitivity Analysis of the Normal Growth Rate of the Cultivated Area

Sensitivity Test 2

Similar to the first two sensitivity analysis tests, the model's behavior is assessed in response to changes to the normal reduction rate of the cultivated area. The model is simulated for three runs, with Run 1 serving as the baseline scenario, Run 2 doubling the normal reduction rate to 12%, and Run 3 halving the normal reduction rate to 3%.

In the case of doubling the normal reduction rate to 12%, a number of parameters reacted sensibly to the increased rate by declining proportionally. The cultivated area (Figure 6-27.a), groundwater use, groundwater energy (Figure 6-27.b), groundwater emergy, renewable energy and its emergy (Figure 6-27.c), and non-renewable energy and its emergy (Figure 6-27.d) are among these parameters. Considering the two emergy indicators used in this analysis (i.e., ELR and *%N*), the simulation results indicate varying yet minor behavioral trends. As a result of the rise in the normal reduction rate, the cultivated area declines exponentially, causing a negligible increase in ELR, as shown in Figure 6-27.e. On the other hand, *%N* declines slightly due to a larger percentage reduction (74.9%) in its numerator (*N*) compared to its denominator (*U* with L&S), which declined by 74.4%, as illustrated in Figure 6-27.f. The simulation results indicate that the model is highly sensitive to the increase in the reduction rate in general, although ELR and *%N* were not. The simulation results are illustrated in the figures below, which show the baseline scenario (6%) in Run 1, the increased reduction rate (12%) in Run 2, and the lowered reduction rate (3%) in Run 3.

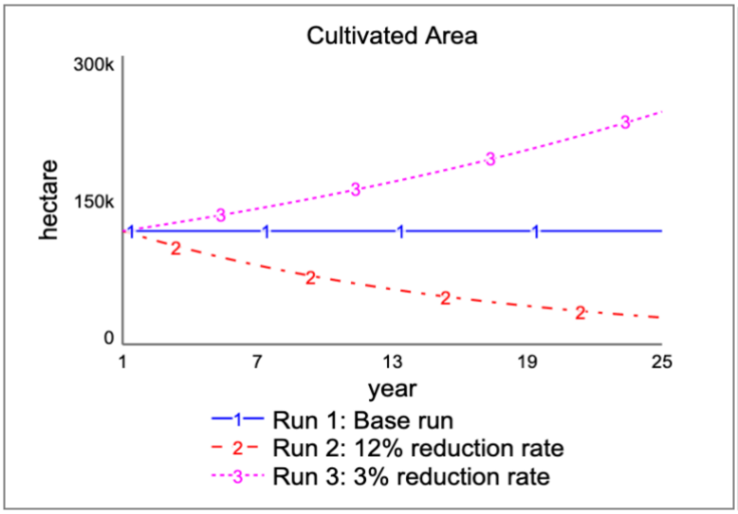


Figure 6-27.a

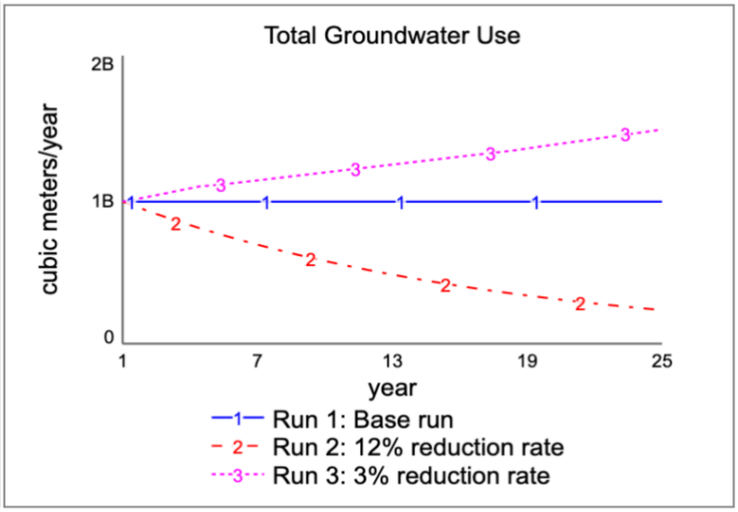


Figure 6-27.b

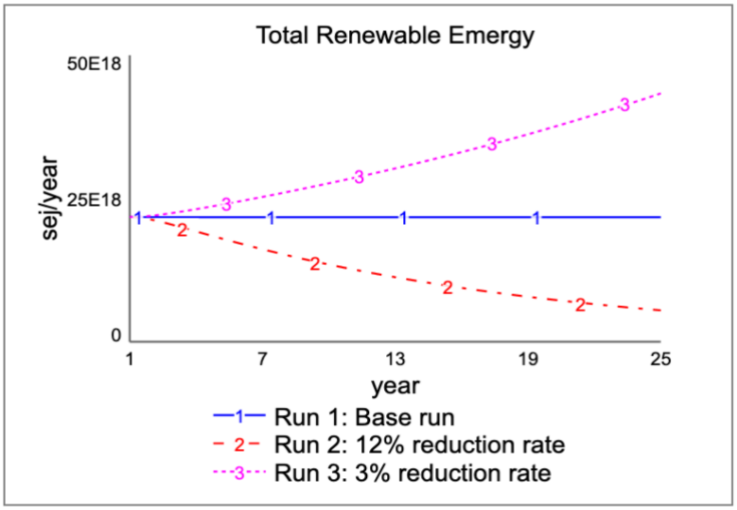


Figure 6-27.c

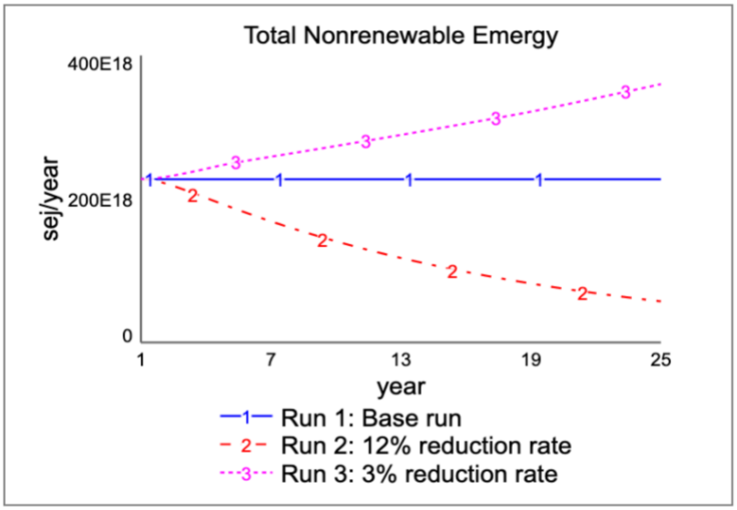


Figure 6-27.d

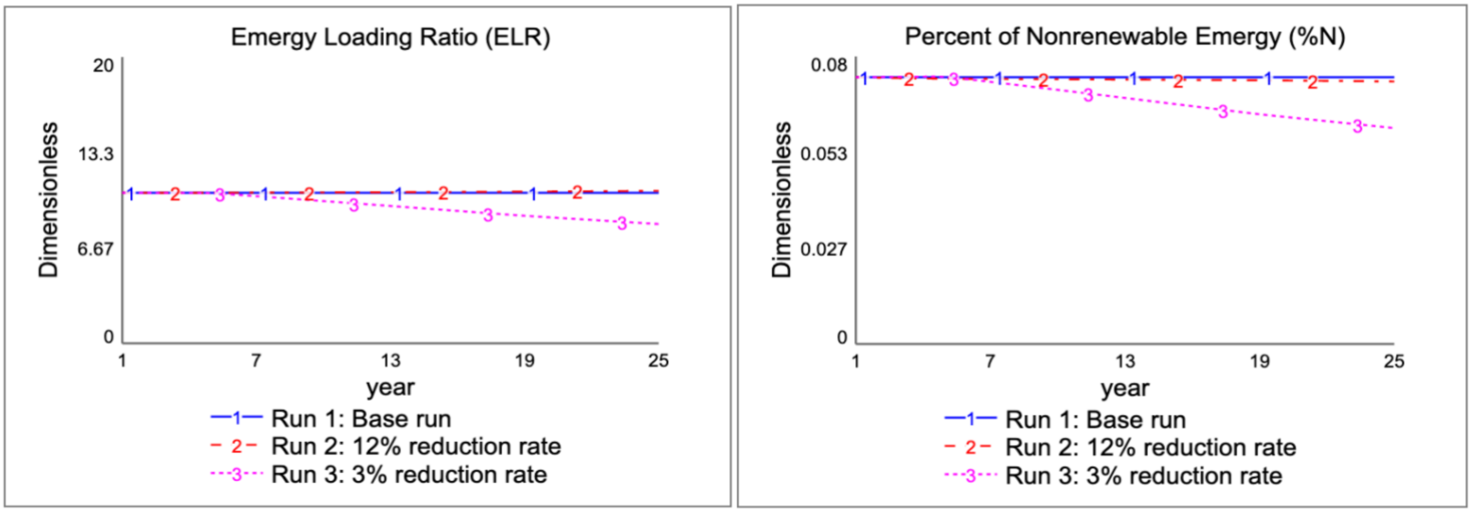


Figure 6-27.e

Figure 6-27.f

Figure 6-27: Sensitivity Analysis of the Normal Reduction Rate of the Cultivated Area

Sensitivity Test 3 and 4

In this section, additional sensitivity analysis tests are performed to assess the model's responsiveness to the implemented policies. With consideration of policy interventions reflected by government subsidy (P1) and environmental concerns (P2), several variables are simulated in the following sensitivity analysis tests. These variables are: normal growth rate, normal reduction rate, normal conversion fraction to drip, normal conversion fraction to flood, and subsidy percentage. Activating the implemented policies in the sensitivity analyses improves the model's validity and creditability. The first set of sensitivity analyses tested the effect of changes in the normal growth rate and the normal reduction rate without considering the impact of policies. For this reason, the effects of normal growth rate and normal reduction rate are tested again with policy interventions.

Sensitivity Test 5

Four scenarios are tested to investigate the model's sensitivity to the effects of P1 and P2. The first run (Run 1) represents the model in a steady state as the baseline scenario. The second run (Run 2) reflects a case wherein the normal growth rate is doubled from 6% to 12% while the impact of government subsidy (P1) and environmental concerns (P2) are included as external pressures. The results show that while the increase in the growth rate caused an increase in the cultivated area (Figure 6-28.a), total groundwater use (Figure 6-28.b), renewable energy and its emergy (Figure 6-28.c), and non-renewable energy and its emergy (Figure 6-28.d), the effect of P1 instigated a change in the area distribution. As shown in Figure 6-28.e, the increase in the cultivated area reduced *%N* from 7.4% to 3.9%, which increased the subsidy from 50% to approximately 91%. Consequently, the cost of drip irrigation dropped to $0.08 per tree, making it more economically feasible to adopt, thereby increasing the drip adoption fraction to 85% of the cultivated area. In addition, the increase in the drip adoption fraction caused the ELR to decline from 10.5 to 5.1 (Figure 6-28.f), raising the relative growth rate and causing exponential growth in the cultivated area. Compared to the baseline scenario, the model is highly sensitive to changes in the normal growth rate and is responsive to policy interventions. The third run (Run 3) assesses the model's sensitivity to the same level of normal growth rate as tested in Run 2 (12%), with the exception that P1 is normalized, suggesting that the cultivated area is evenly distributed between the two irrigation systems while P2 remains in the analysis.

In reference to the baseline run (Run 1), the model remains sensitive to the increase in the normal growth rate even without the effect of government subsidy (P1), which is reflected by the increase in the cultivated area (Figure 6-28.a), total groundwater use (Figure 6-28.b), renewable energy and its emergy (Figure 6-28.c), and non-renewable energy and its emergy (Figure 6-28.d).

Compared to the baseline run, *%N* and ELR also dropped to 3.8% and 5.2, respectively. However, it is worth noting that, regardless of the fact that the drip adoption fraction in Run 3 (50%) is lower than in Run 2 (85%), *%N* and ELR were not significantly influenced by that change, showing a relatively minor change compared to Run 2, as illustrated in Figures 6-28.e and 6-28.f. In other words, excluding the impact of government subsidy (P1) from the third run did not significantly affect the model's behavior when compared to Run 2. Overall, in reference to the baseline, and with consideration of environmental pressure (P2), the model behaves sensitively to the increase in the normal growth rate.

The fourth run (Run 4) reflects the same increase in the normal growth rate (12%) but with imposing the government subsidy policy (P1) and normalizing the effect of environmental pressure (P2). Similar to Runs 2 and 3, the model behaved sensibly to the doubled normal growth rate by showing an increase in the cultivated area (Figure 6-28.a), total groundwater use (Figure 6-28.b), renewable energy and its emergy (Figure 6-32.c), and non-renewable energy and its emergy (Figure 6-28.d). Additionally, *%N* and ELR declined to 4.5% and 6, respectively, as shown in Figures 6-28.e and 6-28.f. Considering the impact of government subsidy (P1), the area distribution changed in favor of the drip irrigation system, increasing from 50% to 83%. However, when compared to the previous two simulation runs (Runs 2 and 3), the level of sensitivity in the fourth run is the lowest, as seen in the figures below. Furthermore, when the two implemented policies (P1 and P2) were actively imposed in Run 2, the model showed the highest sensitivity in terms of the generated behavior, as shown below.

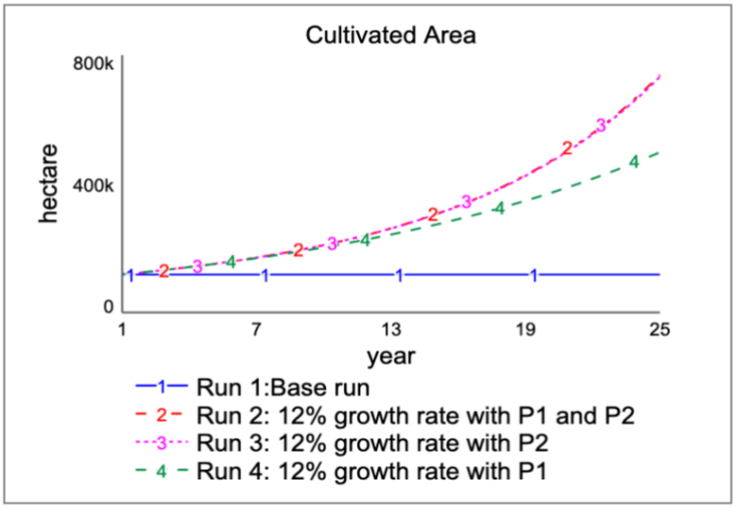


Figure 6-28.a

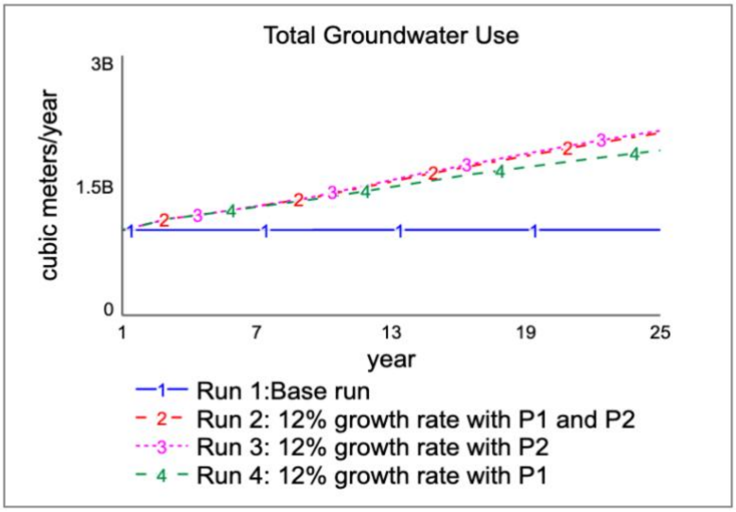


Figure 6-28.b

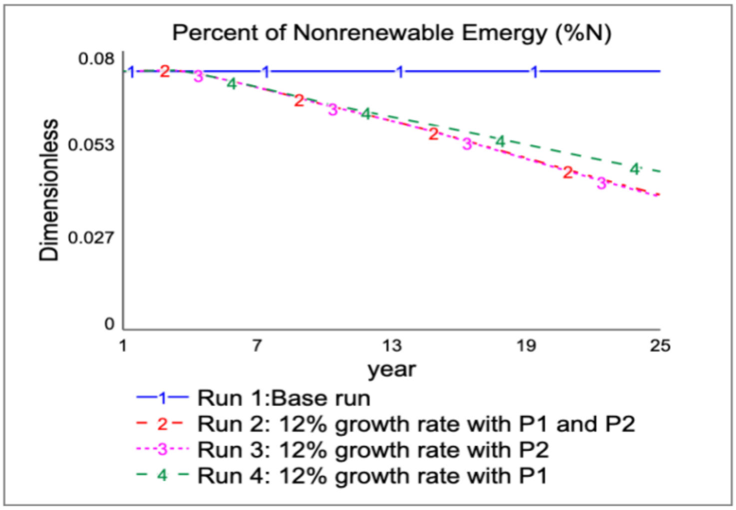


Figure 6-28.c

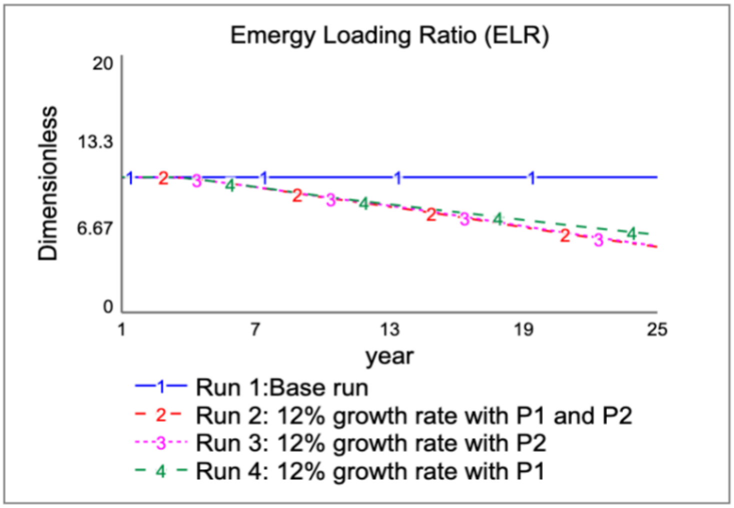


Figure 6-28.d

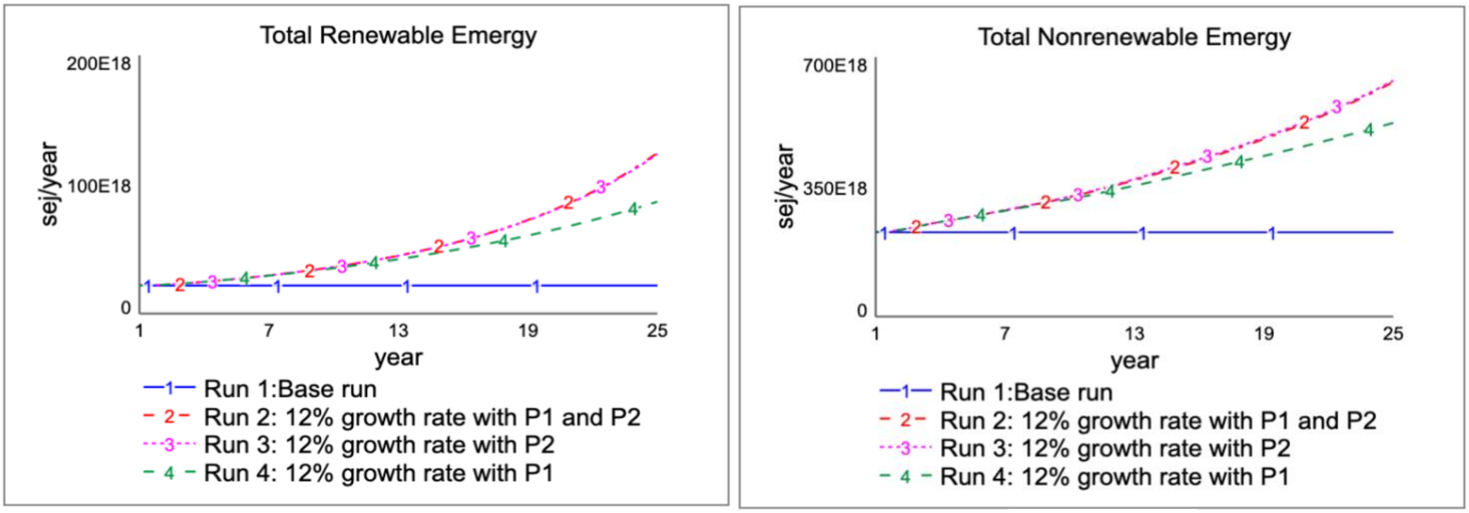


Figure 6-28.e

Figure 6-28.f

Figure 6-28: Sensitivity Analysis of the Government Subsidy Policy P1 and the Environmental Concerns Policy P2

6.6 Policy Intervention

Policy interventions are implemented at a broad level, impacting the upstream activities of Aramco's date seed by-product circular supply chain. This is based on the study by Seles et al. (2016), which suggests that in a multitier supply chain, environmental pressures exerted by the government are transmitted up and down a supply chain, from one tier to the next, stimulating the adoption of sustainable practices.

Saudi is currently working to implement the new 2030 vision which considers sustainable development as part of its goals. According to the Saudi National Portal, the National Environmental Awareness and Sustainable Development Program aims to deal with environmental protection issues. The program points toward increasing public awareness and making environmental problems a priority and promoting environment-friendly practices. Since Aramco is a very large company, its role in implementing such vision is essential. Also, Aramco is under tremendous pressure from regulatory bodies to adopt more sustainable practices (Aramco, 2018).

Thus, Aramco took some corrective actions by developing more sustainable practices in their drilling operations.

Governmental polices (pressures) influence Aramco's supply chain decisions to shift to a circular structure of their supply chain (Aramco, 2018). In accordance to Resolution No. 180 of the Council of Ministers, Aramco stock started trading on the Saudi Stock Exchange on December 11, 2019, providing a potential opportunity for the company to attract international investors. Since some of these investors have a strong commitment to environmental protection, Aramco, as a large local oil company, is all the more motivated to alter the public's perception of the petroleum industry. In fact, in 2018, the Saudi Exchange announced a partnership with the United Nations program for sustainability, the SSE initiative, which emphasizes the importance of the adoption of sustainable practices for all the listed companies. Toward the attainment of the SDG, the Saudi Stock Exchange offers a disclosure agreement of ESG practices for listed companies (SaudiExchange, 2018). As a result, adopting sustainable and circular activities, in this case using by-products, can improve Aramco's environmental footprint. For Aramco, this can be demonstrated as an additional pressure to become more environmentally and sustainably conscious, which raises the importance of using comprehensive environmental performance tools such EA for circular supply chains. In this dissertation thesis, SD can provide insight into the outcomes of such policies over time from emergy and SD perspectives, providing different insights to the decision makers in this supply chain. Based on that, the following two policies are implemented to the emergy SD model at a broad level.

The first policy (P1) represents the effect of government subsidy on the emergy evaluation through an assessment of *%N*, which is incorporated in the model structure within the Emergy Indicators module. The Saudi government issued a ministerial resolution to fund sustainable agricultural practices executed by the Agricultural Development Fund under Royal Decree No. M/9 (2009).

In reference to the scientific environmental definition of emergy indicators (Odum and Odum, 1980), the model proposes that the adoption of P1 is influenced by *%N,* which represents the percentage contribution of non-renewable resources (e.g., groundwater) to date production in general, and to the cultivation of date palm trees in specific. The choice of *%N* as a driver for P1 is supported by recent environmental initiatives launched by the Saudi government under the National Vision 2030 (SAV2030) (Ministry of Environment Water and Agriculture, 2018a), which promotes the use of modern irrigation techniques as a conservation strategy for non-renewable water resources (e.g., groundwater). Furthermore, a number of studies have investigated the impact of agriculture subsidies on irrigation systems in reducing the consumption of groundwater in Saudi Arabia (Abderrahman, 2001; Grindle et al., 2015; Ouda, 2014).

When P1 is activated, the distribution of the cultivated area changes through an increase in the conversion rate from flood to drip irrigation, thereby increasing the drip adoption fraction, which results in reduced consumption of groundwater. In a steady state, the cultivated area is evenly distributed between the two irrigation systems with an adoption fraction of 50% for each technique.

The second policy (P2) reflects the Saudi government's national strategy of increasing date production to achieve food self-sufficiency and increase date exports while preserving natural non-renewable resources (e.g., groundwater) (MEWA, 2020; Ministry of Environment Water and Agriculture, 2018a; The General Authority for Statistics, 2020). When P2 is activated, the normal growth rate of cultivated area is increased. The model assesses the impact of that policy on the level of environmental concerns; testing via ELR will determine whether the policy causes greater environment pressure.

P2 regulates impact of the expansion in date production through assessing the environmental pressure caused by the date production operations. The expansion of the date production is reflected by changes the aggregate cultivated area of date palm trees. P2 is directly linked to the emergy loading ratio (ELR) as an indicator to influence the area growth rate. If P2 causes increasing environmental pressure (ELR), certain measures can be applied to reduce it by decreasing the cultivated area. For instance, the Saudi government has taken similar measures before in an attempt to curb water use by suspending wheat and fodder cultivation (Ministry of Environment Water and Agriculture, 2018a; Royal Decree No. M/66, 2015). Moreover, a study by Naderi et al. (2021) used SD to test several policies, including the management of cultivated area to reduce water stress caused by agricultural activities. The researchers found that reducing the cultivated area resulted in a decline in water consumption. In reference to the scientific environmental definition of emergy indicators (Odum and Odum, 1980), this model uses ELR to assess the impact of P2. The value of the ELR corresponds exclusively to changes in the consumption of renewable and non-renewable resources, which causes a change in the relative increase rate.

Within the agricultural sector, another important element of the National Vision 2030 (SAV2030) is the reduction of environmental pressure while also maintaining a certain level of food security through the production of certain crops (Ministry of Environment Water and Agriculture, 2018a). Furthermore, because dates represent one of the main crops produced in Saudi Arabia, expanding their production contributes significantly to the country’s food security strategy

(Food and Agriculture Organization of the United Nations, 2020; The General Authority for Statistics, 2020).

In general, SD has been used to examine the effect of government subsidy policies on the development of environmentally sustainable practices across multiple levels of analysis. For instance, SD modeling has been employed to investigate the impact of subsidy policies at the urban level (Li et al., 2020; Ye et al., 2021), industry level (Eker and Van Daalen, 2015; Hsu, 2012; Kuo et al., 2019; Wang et al., 2021), and supply chain level (Li et al., 2020; Y. Liu et al., 2018; Preisler et al., 2013; Tian et al., 2014). Relating to irrigation and water management techniques as well as the adoption of sustainable practices within agriculture, a number of studies have used SD to emphasize the role of government subsidies in enhancing water management practices and promoting the adoption of modern irrigation techniques (Cremades et al., 2015; Pluchinotta et al., 2018; Tian et al., 2014). The impact of environmental protection policies on natural resource consumption has also been investigated using SD modeling; such policies were shown to improve utilization of natural resources (Li et al., 2012; Zhang et al., 2014).

6.7 Model Simulation

The purpose of this emergy SD model is to investigate the performance of a Saudi Arabian date production supply chain by adopting a donor-side approach. The model's structure captures multidimensional inputs to the system, including natural and economic resources, and transforms them to emergy values. Then, through a set of causal relationships, dynamic behavior is generated, thereby expanding the emergy evaluations beyond linear measures.

In this emergy SD model, the performance of date production in Saudi Arabia is evaluated using two emergy indicators, *%N* and ELR, comparing flood and drip irrigation systems as the most commonly used irrigation techniques. Higher values indicate high environmental pressure due to excessive usage of non-renewable resources such as soil and groundwater, with greater focus on groundwater due to its scarcity and vitality to the agricultural sector. According to data published by the The National Center for Palms and Dates (2018b), flood irrigation consumes approximately 17.3% more groundwater per date palm tree when compared to drip irrigation. Hence, the Saudi government has implemented regulatory actions to promote drip irrigation as a more sustainable practice to reduce the consumption of groundwater, which is a scarce local non-renewable resource.

Four simulation runs are performed to investigate the impact of policy interventions on the investigated irrigation system through emergy evaluations. The first is a baseline scenario to establish a reference point for all the tested scenarios, reflecting the current situation in which both flood and drip irrigation systems are applied equally with a 50% application rate. The second is the desired scenario in which regulatory actions expand drip irrigation and restrict flood irrigation while maintaining the same cultivated area by normalizing the effect of P2. This scenario aligns with the Saudi government's real-world policy under National Vision 2030 and tests the effect of increased government subsidies supporting sustainable agricultural practices. The third scenario compares the two irrigation systems' performance under the expansion of area under date cultivation (P2), only while maintaining the current distribution of area in terms of adoption fraction via normalizing the effect of P1. This scenario investigates the viability of the government's decision to expand date cultivation in an attempt to maintain a certain level of food security by increasing the area's normal growth rate (Food and Agriculture Organization of the United Nations, 2020). The fourth scenario explores the effect of expanding drip irrigation as an outcome of the imposed regulatory actions (P1) while considering environmental pressure (P2) as an external force affecting the model’s dynamic. In this scenario, both polices (P1 and P2) are actively impacting the model’s behavior.

Baseline Scenario and Second Scenario Simulation Run

To track and assess changes in the SD model’s behavior, and to assess the scenarios and hypotheses, the results of each simulation run are graphically compared to the baseline run over a 25-year period, taking into account the model’s emphasis on investigating natural resource (i.e., groundwater) behavior (Margat et al., 2006).

The second scenario tests the case wherein drip irrigation systems are expected to be widely adopted as a result of government subsidy (P1) (Section 6.6) while maintaining the same cultivated area (P2 is disabled). The second scenario is tested by doubling the normal conversion fraction for drip irrigation from 5% to 10%. Figure 6-29 shows the behavior generated as a result of the second scenario.

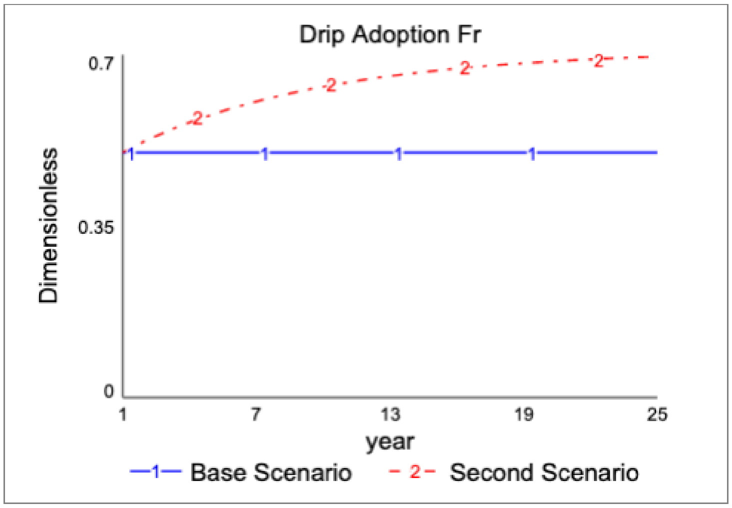


Figure 6-29.c

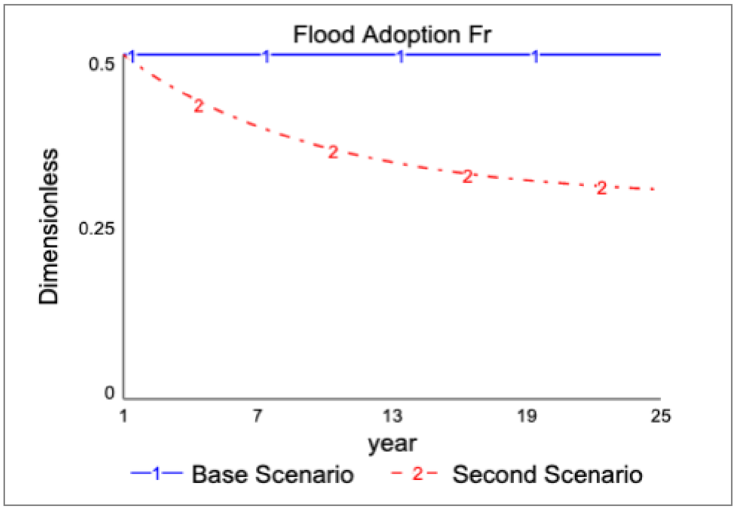


Figure 6-29.d

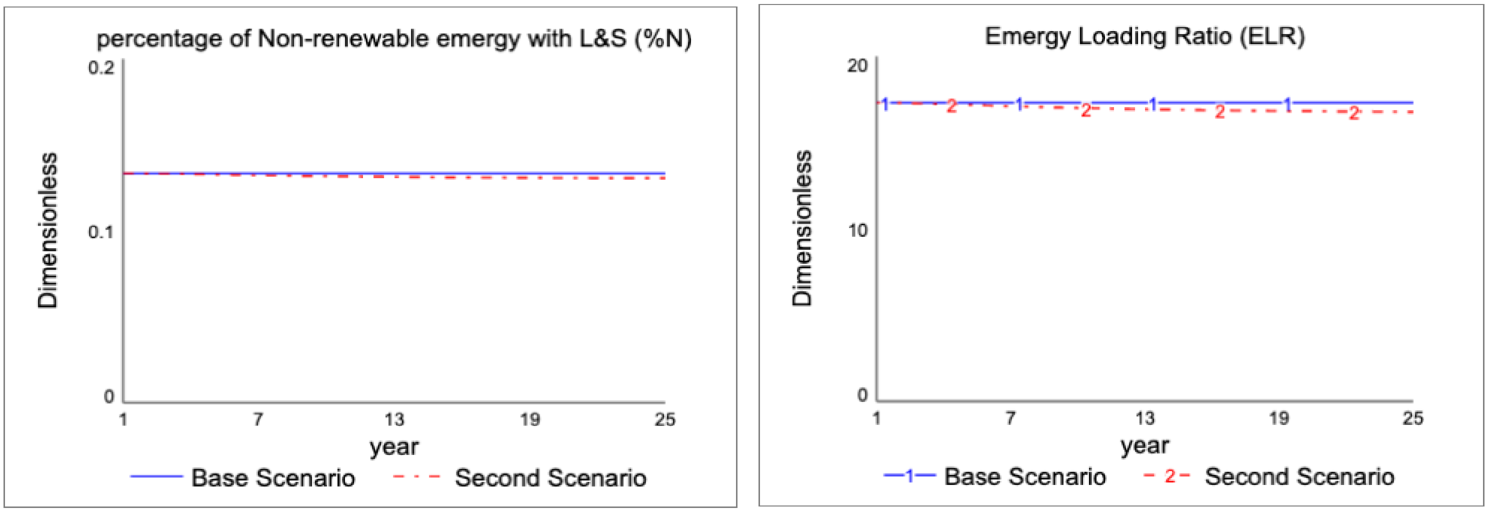


Figure 6-29.c

Figure 6-29.d

Baseline Scenario: Normal conversion fraction for drip irrigation 5%.
Second Scenario: Normal conversion fraction for drip irrigation 10%.

Figure 6-29: Simulation Run of the Second Scenario

Baseline Scenario and Third Scenario Simulation Run

The third scenario is tested by doubling the cultivated area’s normal annual growth rate from 6% to 12%. Figure 6-30 illustrates the behavior generated by implementing the government’s environmental concerns policy (P2) described in Section 6.6.

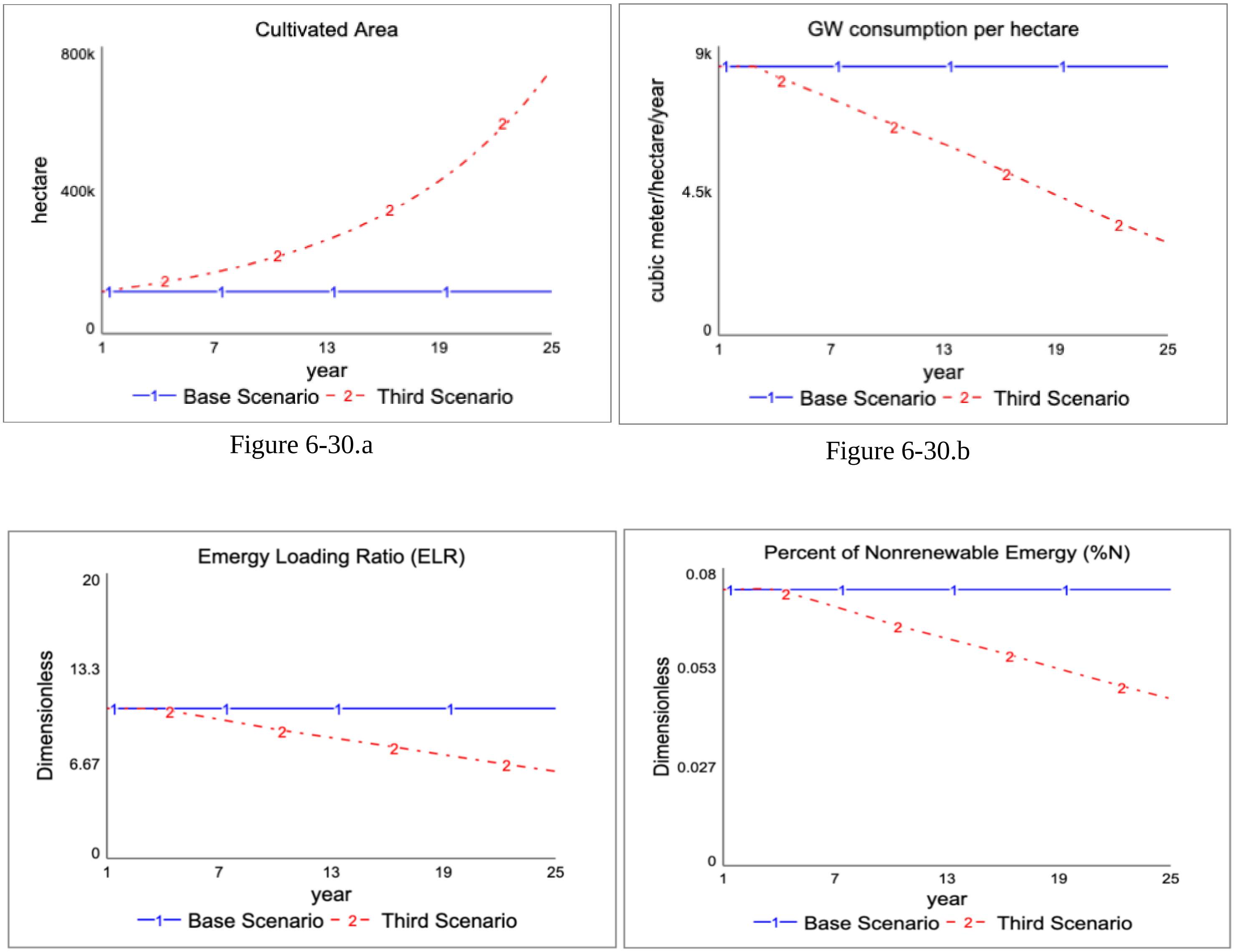


Figure 6-30.a

Figure 6-30.b

Figure 6-30.c

Figure 6-30.d

Baseline Scenario: Cultivated Area Normal Growth rate 6%.
Third Scenario: Cultivated Area Normal Growth rate 12%.

Figure 6-30: Simulation Run of the Third Scenario

Baseline Scenario and Fourth Scenario Simulation Run

The fourth scenario results reflect when both policies, government subsidy (P1) and environmental concerns (P2), are implemented as intervention measures to promote the development of date production sustainability. To disrupt the model's steady state, the same changes are applied to the drip adoption fraction in scenario 2 and to the normal growth rate in scenario 3. The main difference of this fourth scenario is that it simultaneously activates the effects of both proposed policies to assess the level of improvement when both policies are considered. The results of the fourth scenario are illustrated in Figure 6-31 (a, b, and c).

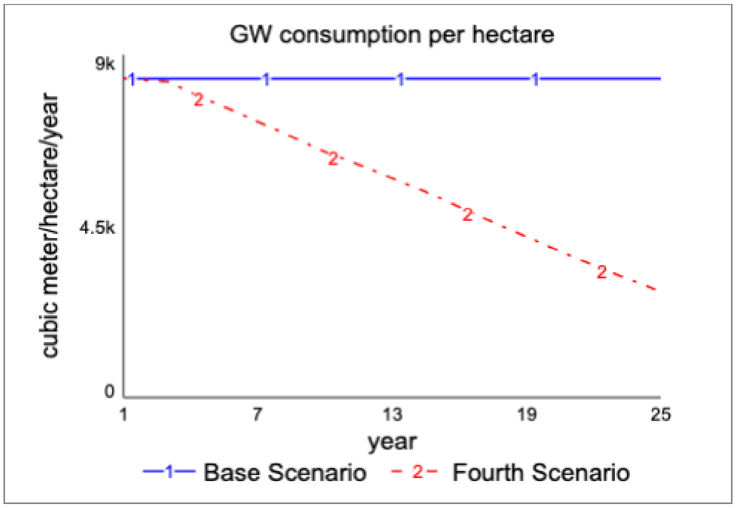


Figure 6-31.a

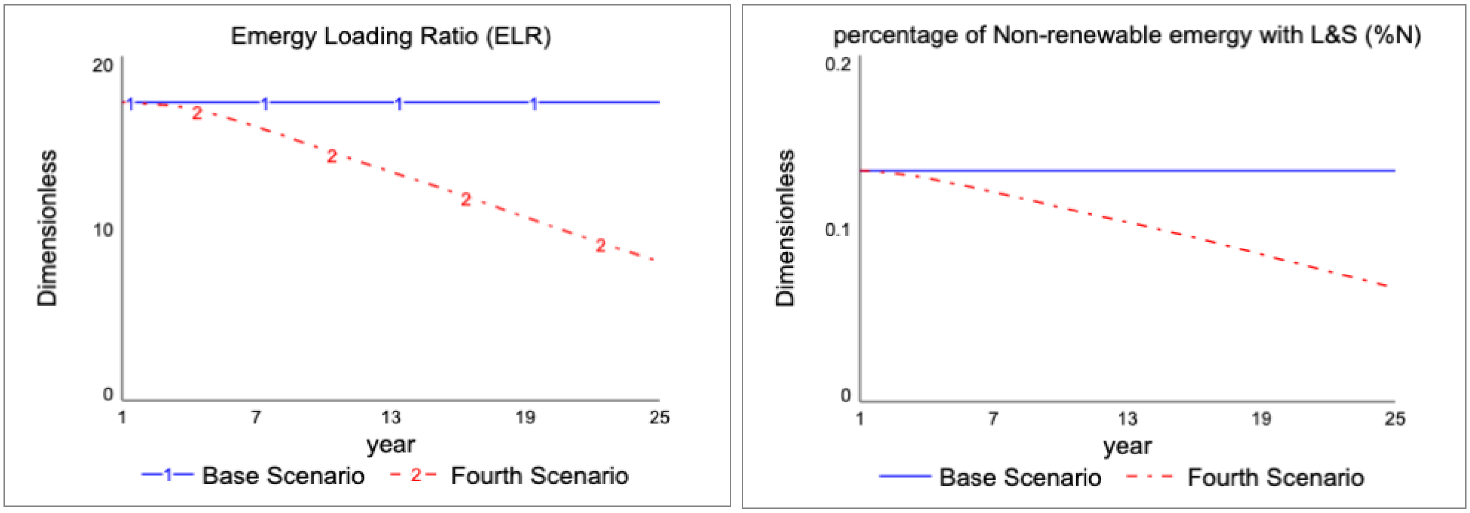


Figure 6-31.b

Figure 6-31.c

Base Scenario: normal conversion fraction for drip irrigation 5%
and
cultivated area normal growth rate 6%.

Fourth Scenario: normal conversion fraction for drip irrigation 10%
and
cultivated area normal growth rate 12%.

Figure 6-31: Simulation Run of the Fourth Scenario

The results of the baseline, second, third, and fourth scenarios will be presented and thoroughly analyzed in Chapter 7, highlighting the impact of each policy on the emergy SD model's behavior as informed by NRDT constructs.

CHAPTER 7 : RESULTS AND DISCUSSIONS

This chapter includes the results and findings obtained from the emergy analysis (EA) and system dynamics (SD) analytical evaluations from Chapters 5 and 6, respectively. Section 7.1 provides aggregated emergy evaluation results with a comparative performance evaluation of the date seed and walnut shell by-product supply chains. The performance analysis will utilize emergy-based indicators that map to natural resource dependence theory (NRDT) constructs. Section 7.2 then presents the simulation results of the emergy SD model of date cultivation activities within the date seed by-product supply chain. These results are then extrapolated onto the entire date seed by-product supply chain. Section 7.3 further discusses the results and findings, as well as initial relationships to the theory, research questions and hypotheses, which are more briefly introduced here in Section 7.1.

7.1 Emergy Evaluation Results

Table 7-1 summarizes the results obtained from the extensive emergy evaluations of the date seed and walnut shell by-product supply chains presented in Chapter 5. The emergy evaluations of date cultivation, date transportation, and date seed by-product processing are conducted in Sections 5.1, 5.3.1, and 5.4, respectively, with all the detailed calculations presented in Tables 5-1, 5-3, 5-6, 5-6, 5-7, 5-8, 5-9, and 5-10. Additionally, the emergy evaluations of walnut cultivation, walnut shell transportation, and walnut shell by-product processing are performed and presented in Sections 5.2, 5.3.2, and 5.5, respectively. All related emergy calculations and values are presented in Tables 5-2, 5-4, 5-11, 5-12, 5-13, 5-14, and 5-15.

Table 7-1: Emergy Evaluation Results Summary

Supply Chain Phase	Dates Seed Supply Chain	Walnuts Shell Supply Chain	Difference	% Change
Cultivation				
Renewable resources, R (sej/yr)	2.18E+19	3.81E+19	-1.63E+19	-75%
Non-renewable resources, N (sej/yr)	2.27E+20	1.95E+20	3.20E+19	14%
Imported/Purchased resources, IM (sej/yr)	1.87E+20	1.53E+20	1.02E+18	18%
Total emergy without L&S (sej/yr)	4.36E+20	2.86E+20	1.70E+19	34%
Total emergy with L&S (sej/yr)	3.28E+21	2.97E+20	2.85E+21	91%
Mass produced (g/yr)	1.54E+12	6.76E+11		
Specific emergy without L&S (sej/g)	2.83E+08	5.71E+08	-1.83E+08	
UEV without L&S (sej/J)	2.16E+04	2.63E+04	-3.20E+03	
Transportation				
Imported/Purchased resources, IM (sej/yr)	2.52E+16	1.50E+17	-1.64E+17	-495%
Specific emergy of transported by-product without L&S (sej/g)	6.49E+07	3.87E+08	-4.22E+08	
UEV without L&S (sej/J)	5.28E+03	1.99E+04	-2.10E+04	
By-product processing				
Imported/Purchased resources, IM (sej/yr)	5.56E+17	1.38E+18	-8.24E+17	-148%
Specific emergy of processed date seeds without L&S (sej/g)	7.99E+08	1.72E+09	-9.21E+08	
UEV without L&S (sej/J)	3.97E+04	8.92E+04	-4.95E+04	

Table 7-1 presents some key emergy values for the two supply chains' upstream and downstream stages. It is important to highlight that the cultivation of dates and walnuts is the only phase of their respective supply chains that consumes renewable resources. Compared to dates, walnut cultivation consumes a greater proportion of renewable resources, with a renewable emergy of 3.81E+19 sej/year, whereas date cultivation consumes approximately 75% less emergy from renewable resources. Date cultivation's lower consumption of renewable resources (2.18E+19 sej/year) is attributed to the harsh climate and geographical characteristics of Saudi Arabia as a date-growing region. By contrast, walnuts are produced in the United States, where natural resources are more plentiful and diverse.

The emergy evaluation for the broader date seed by-product CE supply chain and its comparison to the walnut shell by-product supply chain yielded some unexpected outcomes. Walnut shells utilize a global supply chain and are imported from the US in accordance with international trade laws. Date seeds, by contrast, are local by-products and as such utilize a more localized supply chain. Initial assumptions tend to favor date seed by-products as the more sustainable alternative, as indicated in Hypothesis 1, which states: "*Because they are a local source, date seed supply as a by-product is more sustainable than walnut shell supply from an emergy perspective.*"

Due to the paucity of renewable resources, date cultivation consumes 14% more non-renewable emergy than walnut cultivation. As for the emergy of purchased resources, date production is more dependent on resources imported from outside the system's boundary. The last two emergy values—specific emergy value (without L&S), which measures the degree of environmental required to produce a product, and UEV (without L&S), which measures the intensity of energy transformations to produce a product—are greater for walnut cultivation than for date cultivation, shifting the equation slightly in favor of date cultivation. The specific emergy value (without L&S) suggests that the quantity of walnut production is not proportional to the emergy required for its cultivation. This is important when considering supply chain-related decisions because ignoring other aggregate measures, such as emergy-based indicators, may result in misleading aassessments of the supply chains under study. The higher UEV indicates that walnut cultivation requires more energy and environmental activities than date cultivation. If we were to rely on the values of these two measures—specific emergy value and UEV—we could conclude that date cultivation is more sustainable than walnut cultivation. However, the aggregate performance measures are more reliable in forming reasonable supply chain decisions; this is what distinguishes emergy as a performance measure over other traditional measures (e.g., economic measures).

As for the emergy evaluation of both by-product supply chains' transportation systems, results reveal that the transportation of date seed throughout its local supply chain has lower purchased resources emergy (Table 2-1) (IM), specific emergy, and UEV values when compared to the transportation of walnut shells. Although this is expected because the intensity (UEV) of the activities carried out to deliver a product within a local supply chain is logically lower than that of a global supply chain, the focus of this research is to evaluate the supply chain from the point of production of the raw source of the by-products (dates and walnuts) until the point of transforming them into lost circulation materials.

The final tier of the supply chains under study is the processing of their respective by-products. Similar to the emergy of transportation, processing date seed by-products resulted in lower IM, specific emergy, and UEV. Although these emergy values may provide some general indication of the performance of both supply chains, the key evaluation criteria are based primarily on the emergy-based indicators, which are described in the next section.

Table 7-2 summarizes the results of the emergy indicators obtained through the extensive emergy evaluations of the date seed and walnut shell by-product supply chains; all calculations are shown in Chapter 5, Table 5-16. The results include a set of emergy-based indicators of the cultivation processes, transportation systems used to deliver the by-products, and the six manufacturing processes performed by Saudi Aramco. These measures are defined and explained in Chapter 2, Section 2.4, Table 2-1. Calculations of the presented emergy indicators in Table 7-2 are provided in Chapter 5, Table 5-16.

Table 7-2: Emergy-based indicators of the date seed by-products supply chain and the walnut shell by-products supply chain.

Emergy Indicators	Description	Date Seed Byproducts	Walnut Shell Byproducts
ELR	A measure of the environmental pressure caused by a system's operations. The lower the ELR the lower the environmental pressure. (Odum, 1996)	19	9
ESI	A measure of the sustainability of a product or a system. ESI<1 indicates a non-sustainable product/system. ESI>1 indicates a long-term sustainable product/system. (Brown and Ulgiati, 2002)	0.12	0.28
EYR	A measure of a system's efficiency in exploiting local resources The higher the EYR, the higher the efficiency level of using local resources. (Guo et al., 2023)	2.33	2.52
EIR	A measure of the utilization level of local natural resources. The lower the EIR, the higher the utilization level of the free available natural resources. (Odum, 1996)	0.75	0.65

The emergy-based indicators integrate the performance of the evaluated systems from the point of origin of the by-products to the final processing steps to produce upcycled products that can be used in value-added processes.

The overall results of the emergy indicators do not support Hypothesis 1 (Chapter 3, Section 3.4), which states: "*Because they are locally sourced, date seed supply as a by-product is more sustainable than walnut shell supply from an emergy perspective*." All the values of the emergy indicators indicate that the walnut shell by-products are more sustainable than date seed by-products. Therefore, Hypothesis 1 is not supported by the results.

The first indicator is the emergy loading ratio (ELR), which measures the environmental pressure caused by a system's operations; the higher the ELR value, the higher the environmental pressure (Odum, 1996). ELR is calculated by dividing the sum of the emergy of non-renewable resources and purchased resources by the emergy of renewable resources: *((N+IM)/R)*. For the date seed supply chain, ELR is 19, which is 53% higher than the ELR of the walnut shell supply chain, indicating that the production of date seed by-products imposes a significantly greater environmental burden than the production of walnut shell by-products. The reason for this gap between the two ELRs is that date cultivation relies more heavily on the use of non-renewable resources, such as groundwater and soil. The ELR measure is used to test Hypothesis 2, defined and developed in Chapter 3, Section 3.4, which states: *"The date seed by-product supply chain has a lower environmental pressure on the natural system than the walnut shell by-product supply chain."* The results do not support Hypothesis 2. This hypothesis is tested using ELR as a donor-side measure, which indicates that the walnut shell by-product supply chain imposes less environmental pressure on the natural system than the date seed by-product supply chain. Furthermore, from the perspective of NRDT, the results of the ELR indicate that the date seed by-product supply chain has a greater organizational impact on the natural system than the walnut shell by-product supply chain.

The next indicator is the emergy sustainability index (ESI), which provides an aggregate view of the two supply chains from environmental (ELR) and economic viewpoints (EYR) and is calculated by dividing ELR by the emergy yield ratio (EYR) (Table 2-1). According to Brown and

Ulgiati (2002), an ESI value lower than 1 indicates that the evaluated system is not sustainable in the long term.

Although neither supply chain is operating sustainably in the long term, the walnut shell supply chain has a more promising capability in improving its sustainability. However, the date seed supply chain can still benefit from refining some operational practices to achieve long-term sustainable performance using policy interventions that employ a joint emergy SD approach, which will be presented in the following section.

ESI is also used to evaluate Hypothesis 3 (Chapter 3, Section 3.4), which states: *"The impact of the date seed by-product supply chain on the natural environment is more sustainably responsible than the walnut shell supply chain."* According to the ESI, Hypothesis 3 is not supported, indicating that the walnut shell by-product supply chain is the more sustainable supply chain. Relating that to the NRDT, the ESI values of the two supply chains suggest that the organizational impact of the date seed by-product supply chain on the natural environment is greater than that of the walnut shell by-product supply chain.

EYR (Table 2-1) measures the support a process can offer to the local economy by exploiting local resources and is calculated by dividing all the inputs to the system, $(R + N + IM)$, by the emergy of purchased resources (IM). The greater the EYR, the more support there is for the local economy. The value of the EYR suggests that the walnut shell supply chain is a more efficient way of exploiting local resources compared to the date seed supply chain. Analysis conducted on the date seed supply chain shows a high reliance on imported resources, which negatively impacted its ability to utilize local natural resources $(R + N)$.

Additionally, the EYR is used to test Hypothesis 4 (Chapter 3, Section 3.4), which states: *"Because of better exploitation of local resources, the ecological impact on the walnut shell by-*

product supply chain is higher than that on the date seed by-product supply chain." The EYR's values do not support Hypothesis 4. Specifically, the walnut shell by-product supply chain demonstrates a better exploitation of the local resources when compared to the date seed by-product supply chain. EYR also suggests that because the walnut shell by-product supply chain more efficiently exploits local resources, it is less dependent on the natural environment and faces a lower ecological impact.

Finally, EIR measures the of the "utilization level" of the used emergy (Ren et al., 2015). It is the ratio of the emergy of purchased resources (IM) to the emergy of renewable and non-renewable resources *[(IM/(R+N)]*. Lower values of EIR indicate better utilization levels of the free available emergy (Odum, 1996). EIR results further emphasize that the date seed supply chain improperly utilizes local resources and is highly dependent on imported resources. By contrast, the walnut shell supply chain employs a more effective approach in utilizing the free emergy available in its natural system. This indicator is used to test Hypothesis 5 (Chapter 3, Section 3.4), which states: *"Because of a high utilization level of local natural resources, date seed by-product supply chain is less dependent on the natural environment than the walnut shell by-product supply chain."* EIR values do not support Hypothesis 5 because the results show a higher utilization level of local resources for the walnut shell by-product supply chain as opposed to the date seed by-product supply chain. The EIR also indicates that the walnut shell by-product supply chain is less dependent on the natural environment, and therefore imposes a lower ecological impact than the date seed by-product supply chain.

7.2 System Dynamics Simulation Results

Here we evaluate the emergy SD model and the results of the four scenarios depicted and run in Chapter 6, Section 6.7. A series of SD model runs are executed to evaluate the hypotheses relating to policy implementations and to evaluate the NRDT influences. The first is the baseline scenario, which establishes a reference point for all the tested scenarios, reflecting the current situation in which both flood and drip irrigation systems are applied at a rate of 50%. The second scenario tests the impact of government subsidy (P1) (Section 6.6). The third scenario tests the impact of the environmental concerns policy (P2) under cultivated area expansion. The fourth scenario tests the impact of implementing both policies simultaneously. Specifically, two hypotheses will be evaluated: Hypothesis 6 (Chapter 3, Section 3.4), which states: *"The percentage of non-renewable resources used in the date supply chain is lower due to the impact of a government subsidy policy,"* and Hypothesis 7 (Chapter 3, Section 3.4), which states: *"The environmental pressure is reduced as a result of Saudi Arabia's regulatory environmental actions."*

To track and assess changes in the SD model's behavior and to assess the scenarios and hypotheses, the results of each simulation run are graphically compared to the baseline run over a 25-year period, taking into account the model's emphasis on investigating natural resource behavior (i.e., groundwater) (Margat et al., 2006). The results of these behaviors are shown in Figures 7-1, 7-2, and 7-3, which illustrate the emergy SD model behavior to show the impact of each policy (P1 and P2).

The second scenario illustrates the case in which regulatory actions expand drip irrigation and restrict flood irrigation while maintaining the same cultivated area by normalizing the effect of P2. This scenario aligns with real-world policy enacted by the Saudi government under National Vision 2030, an environmental initiative that promotes the use of modern irrigation techniques to conserve non-renewable water resources (e.g., groundwater) (Ministry of Environment Water and Agriculture, 2018a). This scenario tests the effect of higher government subsidies in support of sustainable agricultural practices. P1 is explained in Chapter 6, Section 6.7.

In the second scenario, flood irrigation systems are restricted because they are considered inefficient in terms of water consumption. The second scenario is tested by doubling the normal conversion fraction for drip irrigation from 5% to 10%. Figure 7-1 (a, b, c, d, e, f, g, and h) summarizes the results of the second scenario.

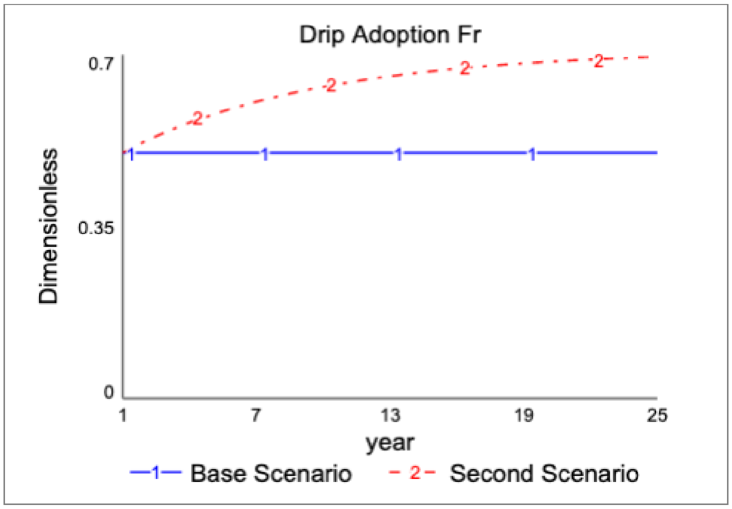


Figure 7-1.a

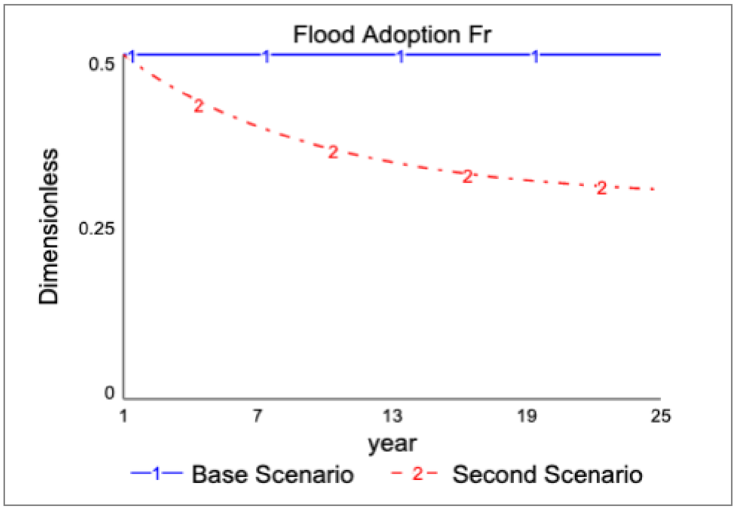


Figure 7-1.b

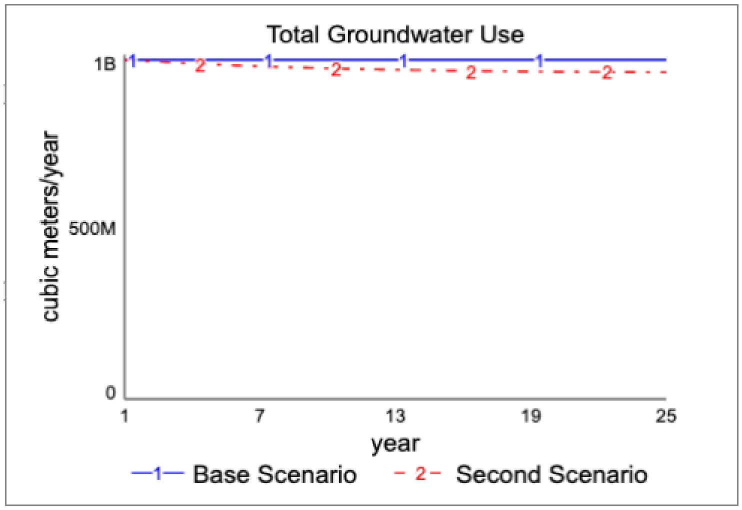


Figure 7-1.c

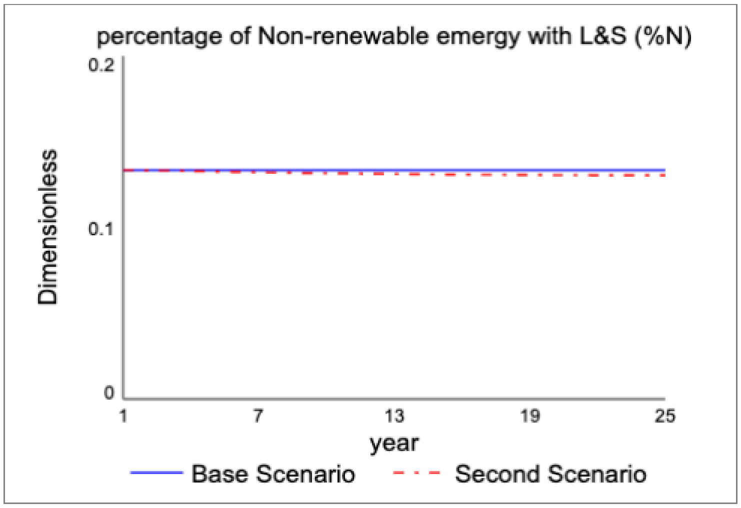


Figure 7-1.d

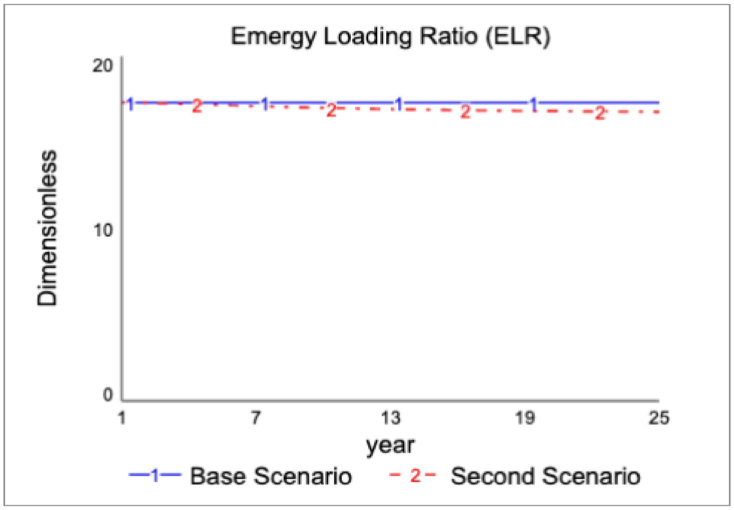


Figure 7-1.e

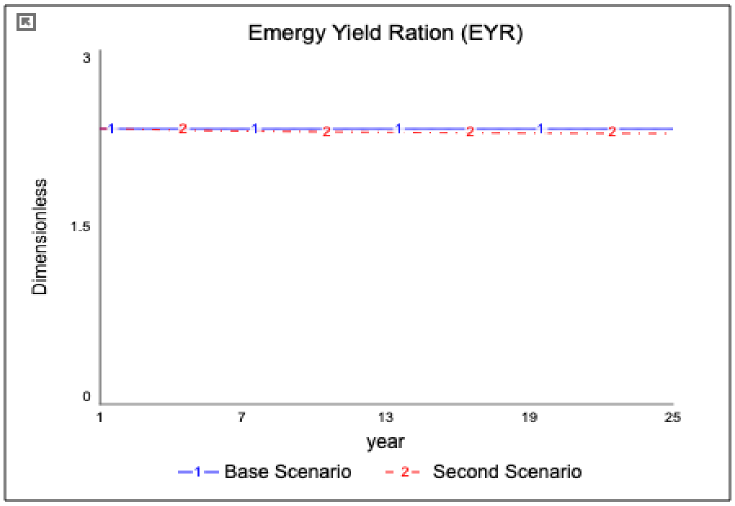


Figure 7-1.f

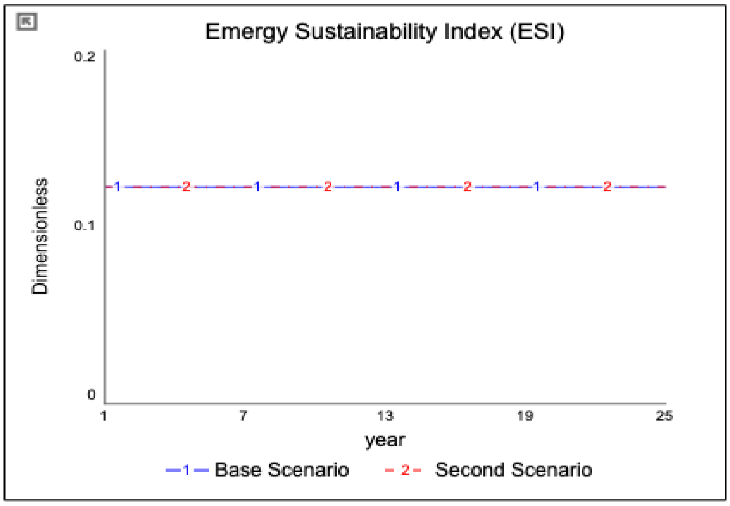


Figure 7-1.g

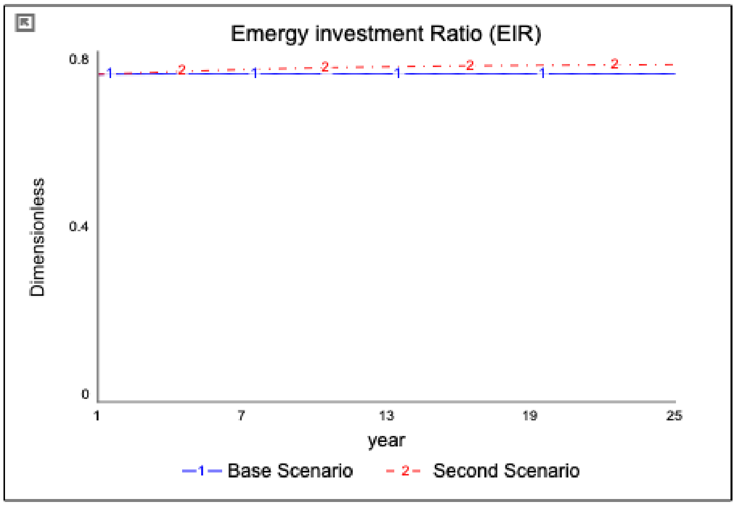


Figure 7-1.h

Baseline Scenario: Normal Conversion Fraction for Drip Irrigation 5%.
Second Scenario: Normal Conversion Fraction for Drip Irrigation 10%.

Figure 7-1: Simulations of the Second Scenario

The effect of doubling the drip conversion fraction increased the drip adoption fraction from 50% to 70% of the cultivated area (Figure 7-1.a). Correspondingly, the flood irrigation adoption fraction declined to 30% (Figure 7-1.b). The expansion of drip irrigation adoption improved overall emergy performance. Because drip irrigation consumes less groundwater per unit of cultivated area, the total groundwater used in drip irrigation falls from 986E+06 m^3/yr to 949E+06 m^3/yr, as illustrated in Figure 7-1.c. As a result, the reduction in the emergy of groundwater means a reduction in the total emergy of non-renewable resources. Therefore, the percentage of non-renewable emergy (*%N*) improved slightly with a small reduction (3.9%), as shown in Figure 7-1.d.

The 2.9% reduction in ELR suggests an improvement in groundwater consumption (Figure 7-1.f), thereby mitigating some environmental pressures caused by excessive consumption. This finding corroborates a study by Song et al. (2014), which found that policies designed to preserve natural resources policies contributed helped reduce the environmental burden (ELR) imposed by a system's operation (in their study, a metabolic system). In general, simulation results of the second scenario indicate that the first policy, government subsidy (P1), improves the system's emergy performance.

From a broader perspective, the analyses can be extended to test the impact of P1 on the remaining indicators, including EYR, ESI, and EIR. The results show that the impact of government subsidy P1 on EYR was very small, with only a slight decrease in its value to indicate a decline of the system's efficiency in exploiting local resources, as shown in Figure 7-1.f. P1 has no impact on ESI, as shown in Figure 7-1.g. Finally, EIR showed a slight increase over time as a result of P1, which indicates a decline in the system's utilization of local natural resources, as shown in Figure 7-1.h. Overall, P1 had a positive impact, reducing both the environmental pressure caused by date cultivation (ELR) and the percentage of non-renewable emergy (*%N*) required by date production.

The third scenario tests the impact of environmental concerns during the expansion of date cultivated area (P2). This scenario is tested by doubling the normal growth rate from 6% to 12% while normalizing the impact of government subsidy (P1). Results are illustrated below in Figure 7-2 (a, b, c, d, e, f, g, h, i, and j).

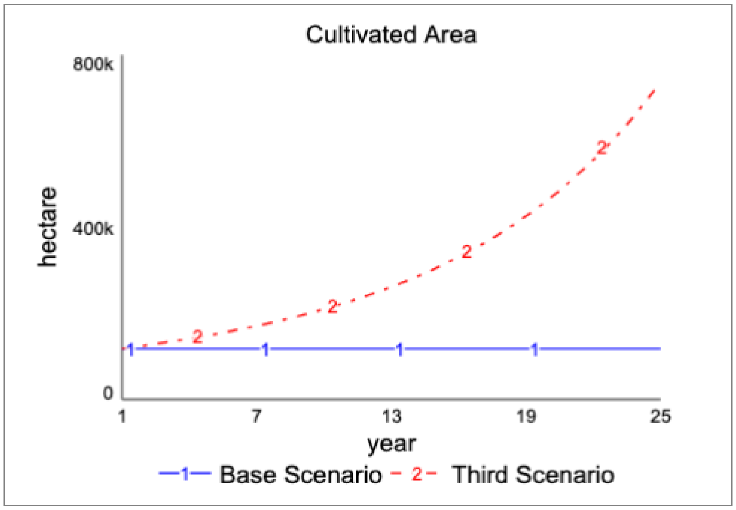


Figure 7-2.a

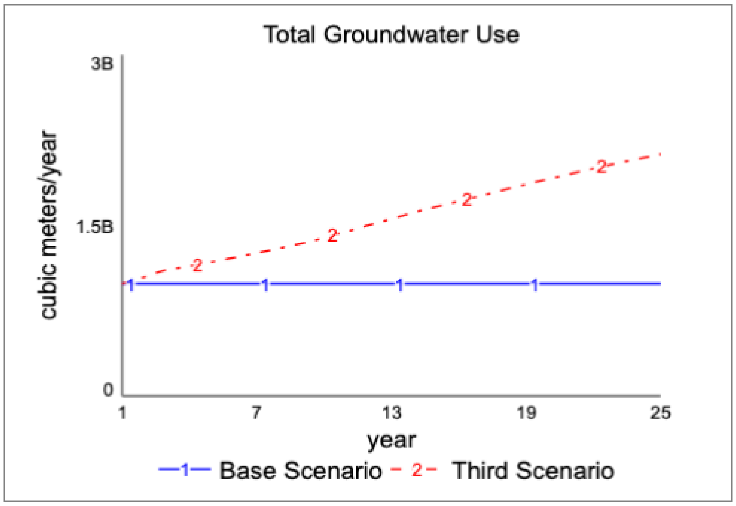


Figure 7-2.b

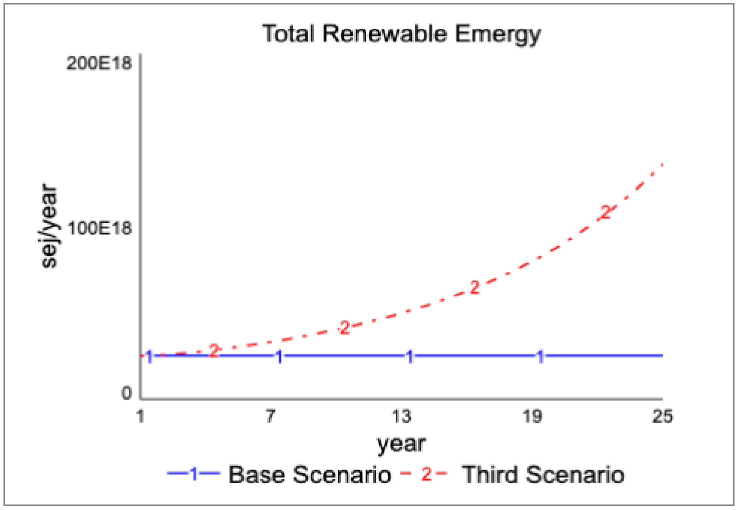


Figure 7-2.c

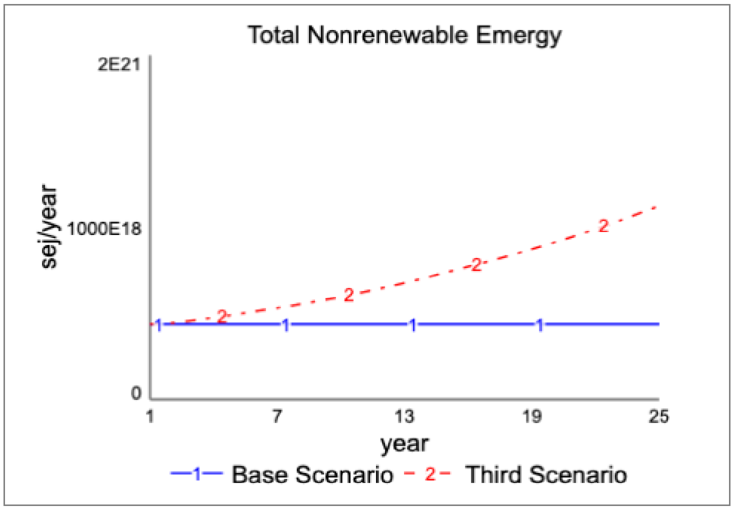


Figure 7-2.d

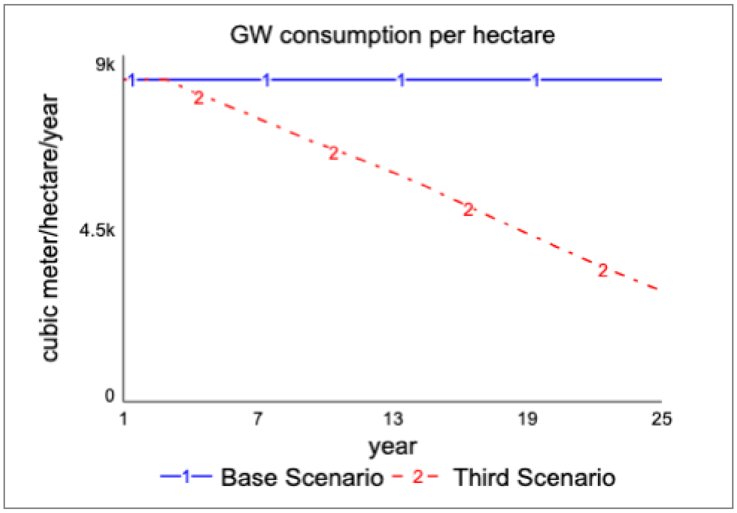


Figure 7-2.e

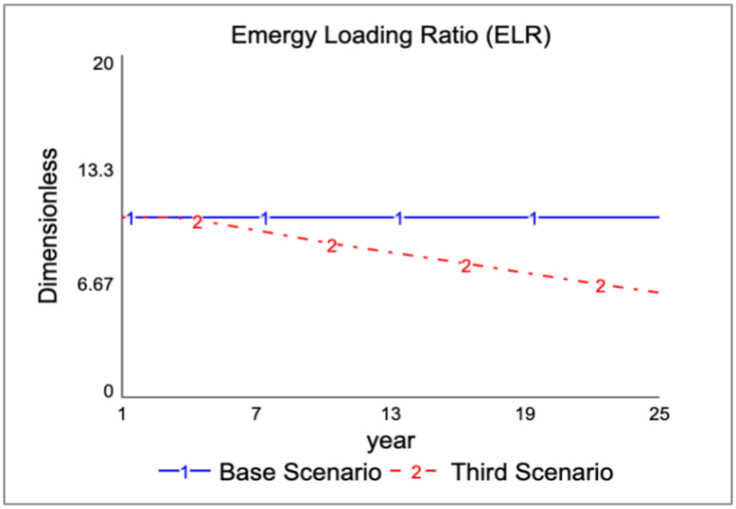


Figure 7-2.f

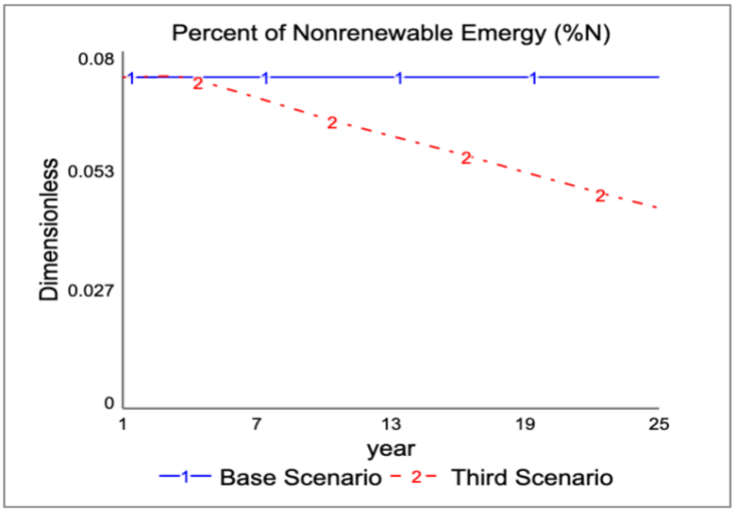


Figure 7-2.g

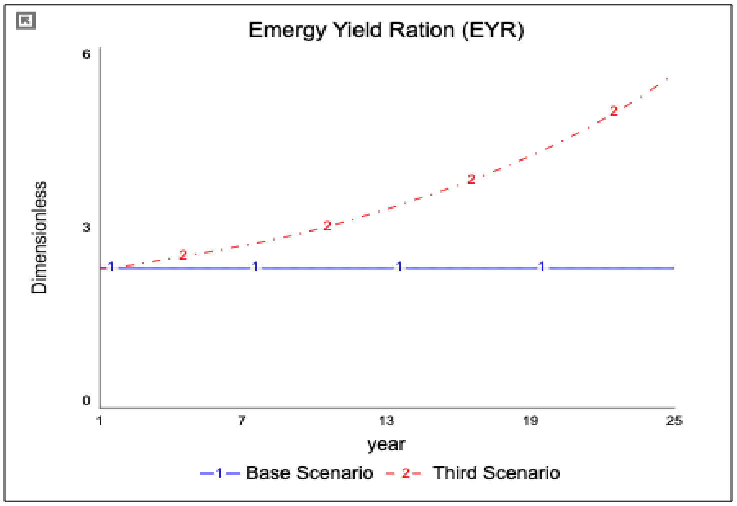


Figure 7-2.h

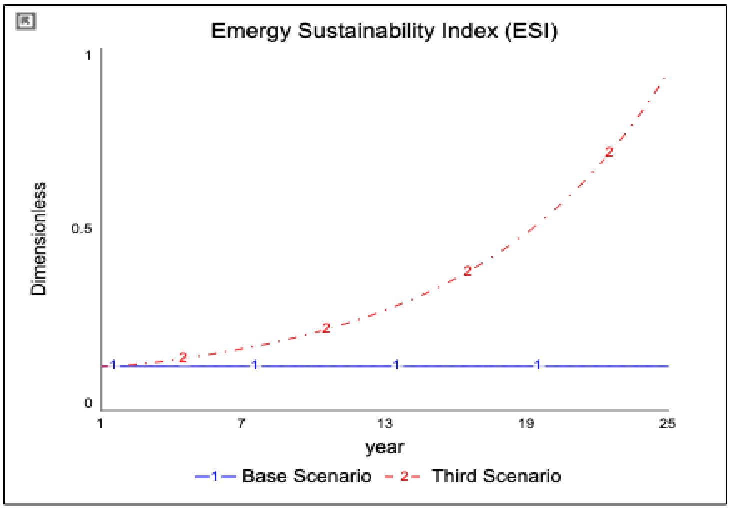


Figure 7-2.i

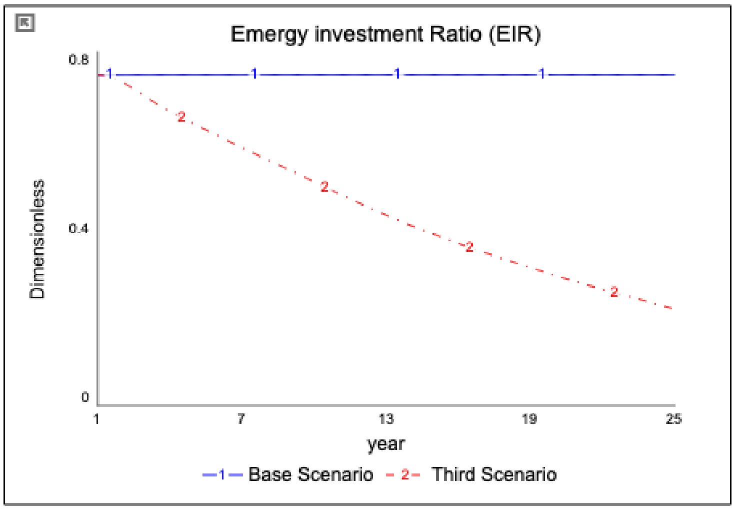


Figure 7-2.j

Baseline Scenario: Cultivated Area Normal growth rate 6%.
Third Scenario: Cultivated Area Normal growth rate 12%.

Figure 7-2: Simulations of the Third Scenario

When the normal growth rate is increased from 6% to 12% in an attempt to expand date production (MEWA, 2020; Ministry of Environment Water and Agriculture, 2018a; The General Authority for Statistics, 2020), the cultivation area grows exponentially, as shown in Figure 7-2.a. Consequently, the total groundwater use also increased (Figure 7-2. b) within the boundaries of acceptable capacity, thereby increasing the total emergy of non-renewable resources (Figure 7-2.d). Furthermore, the rapid increase in the cultivated area raised the total emergy of renewable resources, as shown in Figure 7-2.c.

P2 was shown to cause an increase in groundwater consumption and yielded an even distribution between the two irrigation systems by normalizing the impact of P1; however, the groundwater consumed per hectare declined over time (Figure 7-2.e). This decline in groundwater consumption per hectare results in a reduction in both ELR and *%N*, as shown in Figures 7-2.f and 7-2.g. This result indicates that, although annual groundwater consumption is lower in this scenario, current and future levels of consumption impose additional environmental pressure on Saudi Arabia's local natural environment. The declines in ELR (from 19 to 5.89) and *%N* (from 7% to 3.5%) emphasize the effectiveness of the proposed policy by considering environmental pressure (P2) as a key driver of improved sustainability overall for the date production sector.

The other emergy indicators are all positively impacted by P2. EYR shows a significant improvement from 2.33 to 5.58, as shown in Figure 7-2.h; ESI is improved from 0.12 to 0.94, as shown in Figure 7-2. i; and P2 improved the utilization of natural local resources by reducing EIR from 0.75 to 0.22, as shown in figure 7-2. J.

The fourth scenario simulates the simultaneous implementation of both policies, government subsidy (P1) and environmental pressure (P2), as intervention measures to promote date production while increasing its sustainability. To disrupt the model's steady state, the same changes are applied to the drip adoption fraction in scenario 2 and the normal growth rate in scenario 3. This fourth scenario differs from the other three by simultaneously activating the effects of both proposed policies to assess the level of improvement when both policies are considered. Results of the fourth scenario are illustrated in Figure 7-3 (a, b, c, d, and e).

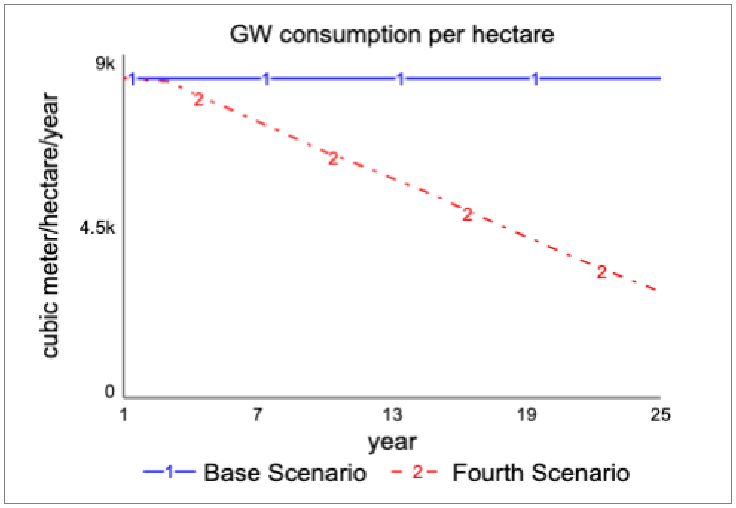


Figure 7-3.a

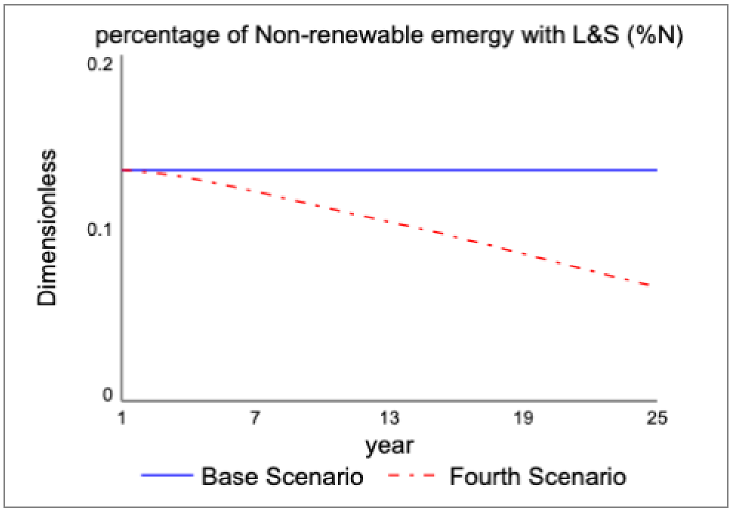


Figure 7-3.b

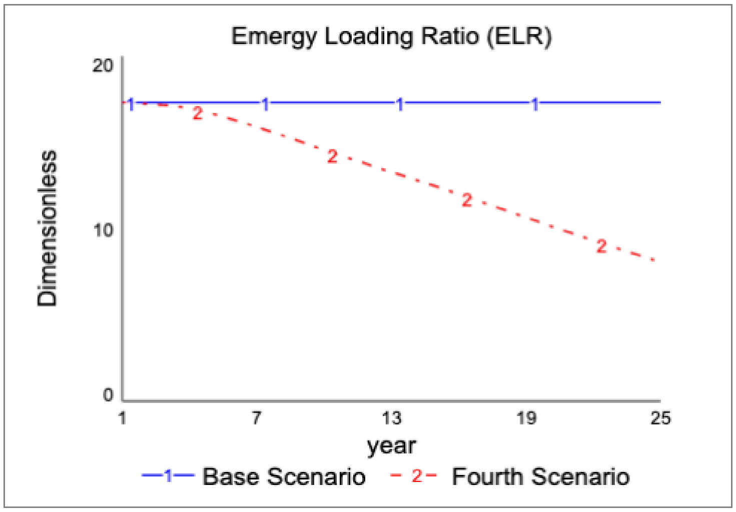


Figure 7-3.c

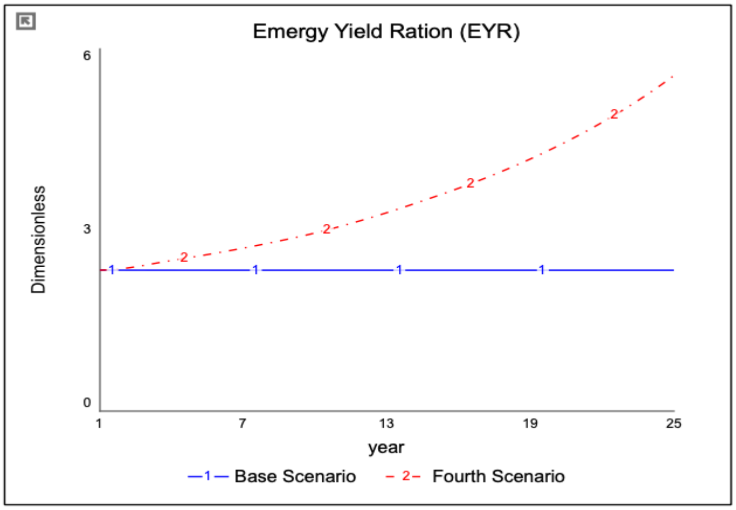


Figure 7-3.d

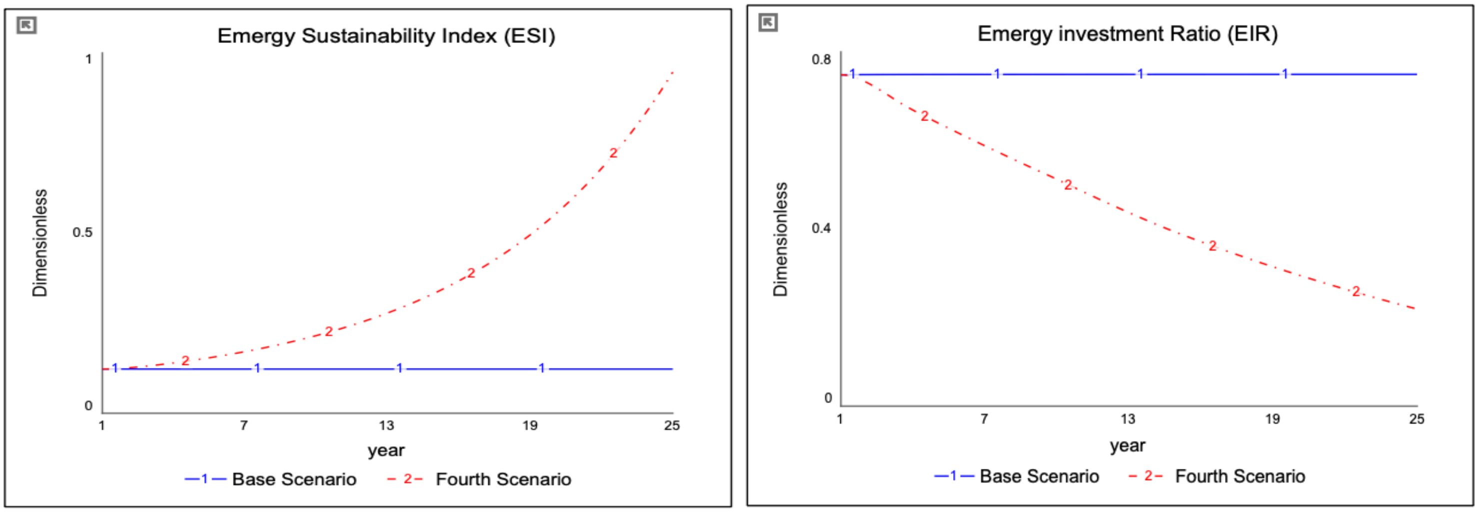


Figure 7-3.e

Figure 7-3.f

Baseline Scenario: Normal Conversion Fraction for Drip Irrigation 5%
and
Cultivated Area Normal Growth rate 6%.
Fourth Scenario: Normal Conversion Fraction for Drip Irrigation 10%
and
Cultivated Area Normal Growth rate 12%.

Figure 7-3: Simulations of the Fourth Scenario

Results of the fourth scenario show the significant impact of synergistic regulatory actions and policies on the sustainability and development of date cultivation practices (Rosenzweig and Tubiello, 2007). More precisely, the implementation of government subsidy (P1) and government pressure (P2) are seen to have a positive impact on date cultivation practices by restricting excessive groundwater consumption and reducing environmental pressures imposed by the supply chain. These results suggest potential synergistic, substitutability, or tradeoffs effects.

In the simulation, incorporating P1 and P2 improved the system’s overall performance in several ways. First, groundwater consumption per hectare declined compared to the baseline scenario, as illustrated in Figure 7-3.a. Government subsidies (P2) to promote conversion from flood to drip irrigation resulted in a 96% adoption rate of drip irrigation, dominating the vast majority of cultivated areas. Compared to the impact of P1 alone, the simultaneous implementation of P1 and P2 yielded a more significant increase in the adoption fraction. This indicates the synergistic impact of these policies, suggesting a complementarity effect (Barry et al., 2019).

The reduction in groundwater consumption per hectare improved *%N*, reducing the contribution of non-renewable resources from 7% to 6.8%, and from that to 3.5% when P1 and P2 were implemented in the fourth scenario, as shown in Figure 7-3.b. However, implementing the two policies simultaneously yielded no further improvement of *%N*, which indicates the presence of a substitutability effect (Cheng and Yi, 2017).

Concerning ELR, as total non-renewable emergy dropped significantly, ELR declined from 19 to 18.7 when P1 was implemented and from 18.7 to 5.97 when P2 was implemented (Figure 7-3.c); this result reinforces the increase in cultivated area and aligns with the government’s strategy of expanding date production as part of the KSA National Vision 2030 (The General Authority for Statistics, 2020). The greatest reduction in ELR is observed when P1 and P2 are simultaneously implemented, indicating a complementarity effect of these policies (Barry et al., 2019).

With regards to EYR, both policies (P1 and P2) have a synergistic impact that improves the system’s efficiency in exploiting local resources, as evidenced by the significant increase in EYR from 2.33 in the baseline scenario to 5.61 when P1 and P2 are implemented (Figure 7-3.d). However, comparing the fourth scenario with the second scenario, it is worth noting that implementing P1 in the second scenario caused a slight reduction in EYR.

Similarly, the highest ESI value was reported when both policies were implemented simultaneously in the fourth scenario (Figure 7-3.e). Comparing that to the second and third scenarios, whereas ESI showed no improvement when P1 was implemented separately (second scenario), it improved significantly when P2 was implemented without P1 (third scenario). This suggests a synergistic effect of simultaneous P1 and P2 policy implementation.

Finally, EIR improved most under scenario 4, emphasizing the synergistic impact of P1 and P2 (Figure 7-3.f). However, when P1 and P2 were implemented separately (second scenario), EIR showed only a slight increase, whereas P2 significantly improved EIR. This suggests another substitutability effect (Cheng and Yi, 2017). Table 7-3 summarizes the four simulation runs, highlighting the main performance indicators under different scenarios.

Table 7-3: Simulation Runs Summary

Variable	Baseline Scenario	Second Scenario (P1)	Third Scenario (P2)	Fourth Scenario (P1&P2)
Groundwater Consumed per Hectare	8.36E+03	8.04E+03	2.47E+03	2.44E+03
Drip Adoption Fraction	50%	70%	50%	96%
Cultivated Area	118E+03	118E+03	891E+03	898E+03
%N	7%	6.8%	3.5%	3.5%
ELR	19	18.7	5.97	5.89
Other Indicators				
EYR	2.33	2.30	5.56	5.61
ESI	0.12	0.12	0.93	0.97
EIR	0.75	0.77	0.22	0.22

A better picture of the examined supply chains can be obtained by integrating the EA results with the SD results. The cultivation activities of date seed and walnut shell by-products have the greatest impact on overall performance, which is measured using a set of emergy indicators that target various aspects of their respective supply chains. Thus, integrating the results of both the EA and the SD analysis provides a number of findings that should be analyzed carefully within the context of the research goals. This means that all seven hypotheses developed in Chapter 3, Section 3.4 are part of the SD simulation experiments under policy intervention. Overall, the emergy SD model supports the theoretical proposition that policy interventions do influence (in this case, positively) an overall improvement of the emergy-based indicators.

According to Seles et al. (2016), using an institutional theory framework, environmental pressures exerted by the government are transmitted throughout a multitier supply chain, from one tier to the next, stimulating the adoption of sustainable practices. Furthermore, Lee et al. (2014) found that environmental requirements tend to be more stringent further upstream the supply chain, which contributes to the level of uncertainty caused by government pressure. This phenomenon, called the "green bullwhip effect," describes the propagation of environmental pressure across the supply chain (Lee et al., 2014) and appears to be directly linked with uncertainty based on governmental regulations. This uncertainty, in turn, relates closely to the theoretical foundations associated with NRDT.

Based on these principles and theory—which relate to the applied theoretical foundation outlined in Chapter 3—this study extends the interrelationships explained by NRDT to address uncertainty caused by government pressure in a circular supply chain setting. The results indicate that, from an emergy perspective, improvements to the environmental performance of the upstream segment of the supply chain translated into better overall performance of a multi-tiered circular supply chain practice. In other words, the analyses provided by the SD model simulations—which are now focused primarily on the cultivation activities of the date seeds as a by-product—can be extended across every tier of the date seed by-product supply chain. The comparative analysis can be expanded to consider the emergy indicators of the date seed and walnut shell by-product supply chains.

Hypotheses 6 and 7 were tested using the emergy SD model. Hypothesis 6 states: *"The percentage of non-renewable resources used in the date supply chain is lower due to the impact* *of a government subsidy policy."* Hypothesis 6 is supported by the *%N* value shown in Table 7-3, which is reduced by the government subsidy promoting the adoption of drip irrigation systems. Considering the NRDT construct, this value for *%N* indicates a case of dependence on natural non-renewable resources. Thus, according to the simulation results of the second scenario, P1 reduces dependence on the natural environment, which also indicates a reduced ecological impact. The principal aim of P1 is to reduce the consumption of groundwater, which is a scarce non-renewable resource in Saudi Arabia.

Hypothesis 7 states: *"The environmental pressure is reduced as a result of Saudi Arabia's regulatory environmental actions."* This hypothesis is supported by the results of the emergy SD model through the ELR values shown in Table 7-3. Comparing the first (baseline) and third scenarios, ELR was improved by regulatory actions related to environmental concerns—namely P2, which reduced the environmental pressure of date cultivation operations by 50%. Moreover, from the NRDT perspective, the improvement of ELR via P2 points to a reduced organizational impact on the natural environment.

Drawing on the simulation results of the emergy SD model, Table 7-4 outlines the key emergy-based indicators against which the two supply chains can be measured. Focusing on the cultivation phase of both supply chains, a substantial improvement in the dates' cultivation emergy performance is observed. Table 7-4 compares the date seed by-product supply chain operating under the impact of P1 and P2 against the walnut shell by-product supply chain.

Table 7-4: Emergy Indicators of the Date Seed By-product Supply Chain under Policy Intervention and the Walnut Shell By-product Supply Chain

Emergy Indicators	Date Seed By-product Without Policy Intervention	Date Seed By-products Under P1 and P2 Impact	Walnut Shell Byproducts	% Change
ELR	19	5.89	9	- 53%
EYR	2.33	5.61	2.52	55%
ESI	0.12	0.97	0.28	70%
EIR	0.75	0.22	0.65	- 195%

As shown in Table 7-4, the ELR of date cultivation in the fourth scenario dropped to 5.89, very nearly matching the ELR value of walnut cultivation. The EYR of fourth-scenario date cultivation increased to 5.61, versus 2.52 for walnut cultivation, indicating that the implemented policies improved the effectiveness of date cultivation operations. This indicates that with the impact of the implemented policies, date cultivation operations consumed more of the available local resources while importing less emergy from the economy. As for ESI, the sustainability of date cultivation operations in the fourth scenario is approximately 70% better than that of walnut cultivation operations under policy interventions. The improved ESI value suggests that the contribution of the date seed by-product supply chain to the local economy outweighs the negative environmental pressure it imposes on the ecosystem. Finally, the EIR of date cultivation under policy interventions is better than that of walnut cultivation, which indicates a higher utilization level of the invested emergy. In other words, because EIR is the ratio of purchased imported resources (IM) to natural resources (N + R) (Odum, 1996), a lower value indicates that the system is effectively utilizing the free emergy.

Although Hypotheses 1, 2, 3, 4, and 5 (Chapter 3, Section 3.4) were developed to include the two supply chains (date seed and walnut shell by-products) evaluated using EA (Chapter 5), the analysis of the simulation experiments can be extended to include these five hypotheses.

The overall improvement of the emergy indicators of the date seed by-product supply chain presented in Table 7-4 compared to Table 7-2 grants broader insights into the systems under study. This result supports Hypothesis 1, which states: "*Because they are locally sourced, date seed supply as a by-product is more sustainable than walnut shell supply from an emergy perspective*." However, Hypothesis 1 was not supported by the emergy evaluations conducted in Chapter 5. The EA results indicated that the walnut shell by-product supply chain remains less sustainable under all policy interventions, as revealed by the values of all emergy indictors (ELR, EYR, ESI, and EIR) shown in Table 7-2.

In a similar manner, the SD simulation experiments provide adequate support for Hypothesis 2, as the ELR of the date seed by-product supply chain has a value of 5.89 compared to 9 for the walnut shell by-product supply chain. This indicates that, under policy interventions, the date seed by-product supply chain imposes less environmental pressure on the natural system than the walnut shell by-product supply chain.

Under the influence of P1 and P2, Hypothesis 3 is also supported, which can be inferred from the ESI value in Table 7-4. The improvement of ESI for the date seed by-product supply chain from 0.12 (Table 7-2) to 0.97 (Table 7-4) indicates that the date seed by-product supply chain's impact on the natural environment is more sustainable than that of the walnut shell by-product supply chain.

Hypothesis 4 is tested by assessing the EYR over time through the SD model under policy interventions. Results show that with the improvement in EYR for the date seed by-product supply chain, the walnut shell by-product supply chain has a higher dependency on natural resources and is thus more susceptible to ecological impact. This provides sufficient support for Hypothesis 4.

The last emergy indictor, EIR, also showed improvement with policy interventions. The EIR of the date seed by-product supply chain decreased from 0.75 to 0.22, indicating better utilization of local natural resources under policy interventions. Comparing the EIR (Table 7-4) of the date seed by-product supply chain (under policy intervention) with that of the walnut shell by-product supply chain, we found that the former has a higher utilization level of local resources and is less dependent on the natural environment. This finding supports Hypothesis 5.

Overall, in emergy terms, the date cultivation supply chain segment performs substantially better under policy interventions than the current performance. Thus, from an emergy perspective, and via the implementation of government subsidy (P1) and environmental concerns (P2), the date seed by-product supply chain is more sustainable than the walnut shell by-product supply chain. Various theoretical and practical implications of the reported results are discussed in greater depth in Section 7.3.

7.3. Discussion

This section discusses the most significant theoretical and practical implications based on the results presented in Sections 7.1 and 7.2 of this dissertation thesis. As part of the theoretical implication a number of research propositions are further developed to provide additional insights that require investigation. The implications and propositions will be based on hypothesis results.

7.3.1 Natural Resource Dependency Theory and Evaluation of Hypotheses Using Emergy Indicators

The results can be linked to the core elements of NRDT, which comprise the direct and indirect relationships between organizations and the natural–ecological systems in which they operate (Tashman, 2011). The NRDT constructs are evaluated from a CE supply chain setting. Specifically, the dependencies of the studied systems are: (1) organizational impact on the natural environment, (2) dependence on the environment; and (3) impact of the natural environment on the organization.

EA provides quantitative donor-side indices to measure these NRDT constructs; this approach is one of this dissertation's principal contributions, and it offers significant research and managerial implications. Indeed, the introduced measures of emergy accounting and analysis methods (which are discussed further below in this section) provide a more objective and comprehensive assessment of the dynamic relationship between organizations and the natural environment. This advantage helps manage critical organizational decisions such as sourcing, resource acquisition, and even supplier selection. For instance, when dealing with supplier selection decisions, this novel use of NRDT constructs with emergy indicators as performance assessment criteria can help identify potential suppliers with less dependence on the natural system, less organizational impact on the natural system, and less natural impact on the organization.

Some general observations can be drawn from the EA results described in Section 7.1. First, contrary to Hypothesis 1 (Chapter 3, Section 3.4), the walnut shell by-product supply chain is more sustainable than that of date seeds. With reference to Section 7.1, Table 7-1, looking at the individual values of each supply chain, the walnut shell by-product supply chain is seen to perform more sustainably at the first stage of the supply chain (i.e., cultivation). On the other hand, the date seed by-product supply chain performs better at the transportation and by-product processing stages when considering the individual emergy values of each input. However, looking at the specific emergy value and the UEV (without L&S) at each stage, we can see that UEV values are lower throughout the date seed by-product supply chain, which means it requires less environmental contribution than the walnut shell by-product supply chain. According to Laganis and Debeljak (2006); Odum (1996), this finding may indicate that the emergy required to produce a certain output is not proportional to its unit mass, which may imply a potentially scarce output in terms of dry mass. Producing 1.54E+12 g of dates each year (Chapter 5, Table 5-1), Saudi Arabia is the world's second largest producer of dates (Alotaibi et al., 2023; The General Authority for Statistics, 2018), whereas the US produces 6.76E+11 g of walnuts each year (Chapter 5, Table 5-2) (USDA, 2020b). Thus, date production exceeds walnut production by more than 50%. Another factor contributing to the reported results is that in both supply chains, cultivation activities are the largest contributor to the total emergy of each system because cultivation is the only stage where natural resources (renewable and non-renewable) are required.

More importantly, it must be noted that the emergy evaluations are applied to different products and by-products with different cultivation requirements and production volumes. Also, the annual production of dates is more than 50% greater than that of walnuts, and both materials have different energy content per gram. All of these factors caused a variation in results between the transformity (UEV) and emergy indicators of each product. As a result, given the observed variation in the results between the specific emergy value and UEV, as well as the results of the emergy indicators, our analysis uses the emergy indicators presented in Table 7-2 to evaluate the systems under study. We follow an approach similar to that used by Eyni-Nargeseh et al. (2023), who relied on emergy indicators to evaluate rice farming systems to compensate for UEV variations.

Emergy evaluations can incorporate NRDT constructs, the first of which highlights the supply chain's impact on the natural system. This construct and direction can be measured through the ELR and ESI emergy ratios. ELR values for both circular supply chains are relatively high, indicating a tremendous environmental burden caused by their operational practices. Environmental burden is considered to be high when the value of the ELR is greater than 10; values between 3 and 10 indicate moderate pressure, and values lower than 3 indicate low environmental pressure (Huo et al., 2022). The impact of both supply chains on the natural system is reflected by the overconsumption of natural resources, especially non-renewable resources such as groundwater (Section 7.1, Table 7-1). Although both supply chains impose high environmental pressure on the ecosystem, the walnut shell by-product supply chain has a lower negative impact (ELR value of 9) compared to the date seed by-product supply chain (ELR value of 19) (Section 7.1, Table 7-2).

Thus, the ELR values for both supply chains do not support Hypothesis 2, which states: *"The date seed by-product supply chain has a lower environmental pressure on the natural system than the walnut shell by-product supply chain."* The development of Hypothesis 1 in Chapter 3, Section 3.4 is built on the fact that Saudi Arabia is the second largest producer of dates, generating around 150,000 tons of date seeds each year (Amanullah et al., 2017; Hamden et al., 2022). With the availability of a local product that has the exact same properties as the imported walnut shells, date seeds are more economically and environmentally viable, as suggested by Saudi Aramco's lead engineer at the Exploration and Petroleum Engineering Research Center, Dr. Amanullah (Amanullah et al., 2017; Amanullah et al., 2016). This is also supported by the literature, where many studies highlight the negative environmental impact of global supply chains in increasing pollution and environmental pressure caused by unsustainable practices in general (Clift and Wright, 2000; Cruz, 2013; Mollenkopf et al., 2010) and transportations in specific, considering the extended travel distance (Levy, 1995).

The donor-side emergy approach provides a unique assessment of the evaluated system that transcends traditional economics-based measures. The emergy evaluations revealed that, although the date seed by-product supply chain operates locally, the agricultural practices adopted during date cultivation activities played a major role in increasing environmental pressure. Table 7-1 provides an overview of that pressure by comparing both supply chains' non-renewable resource emergies. Date cultivation activities require 2.27E+20 sej/year, whereas walnut cultivation requires 1.95E+20 sej/year. The agricultural sector in Saudi Arabia faces tremendous environmental challenges given the scarcity of natural resources—especially water resources—which supports the reported results of emergy indicators (Al-Zahrani et al., 2018; Asirya et al., 2019).

The ESI emergy indicator can also be used to measure a supply chain's impact on the natural system. Results indicate that neither of the two supply chains under study is sustainable in the long term, based on the explanation of ESI by Brown and Ulgiati (2002), wherein ESI < 1 indicates a high level of environmental pressure on the natural system. However, the results revealed that because the walnut shell by-product supply chain has an ESI value of 0.28 (compared to 0.12 for the date seed by-product supply chain) (Table 7-2), the former is more sustainable. This result also indicates that Hypothesis 3 (*"The impact of the date seed by-product supply chain on the natural environment is more sustainably responsible than the walnut shell supply chain"*) is not supported by the ESI. Similar to ELR, sustainable agricultural practices in Saudi Arabia are not fully adopted by farmers for many reasons, such as insufficient awareness of the long-term impact of unsustainable practices (e.g., excessive irrigation) (Al-Zahrani et al., 2018; Othman and Abotalib, 2019; Youssef et al., 2014) and the ineffectiveness of regulations that seek to restrain them (Alotaibi et al., 2020; Napoli et al., 2018). Relating this ESI metric to the NRDT over the two supply chains suggests that the date seed by-product supply chain's organizational impact on the natural environment is higher than that of the walnut shell by-product supply chain.

The remaining NRDT construct is that of ecological impact on the supply chain, which can be measured using emergy-based indicators in much the same way as the first NRDT construct. The EYR and EIR results indicate that both by-product supply chains depend heavily and directly on the natural resources that are available from their natural environment contexts. An EYR value greater than one indicates that both supply chains are highly dependent on natural resources (renewable and non-renewable); EYR also signifies the criticality of utilized natural resources in sustaining supply chain operations, which is an important element of NRDT (Tashman, 2011). Comparing the two EYR values, the walnut shell by-product supply chain has a higher EYR at 2.52, compared to 2.33 for the date seed by-product supply chain. In a study by Corcelli et al. (2018) in which multiple paper production systems are evaluated, the system with the highest EYR

(3.11) was considered to be highly reliant on local renewable and non-renewable resources (as opposed to purchased resources).

High dependence on free natural resources reflects a correspondingly high ecological impact on the operations of the supply chains under study, rendering them more vulnerable to unpredictable natural events that may impact the availability of natural critical resources. It also indicates that in the case of high dependence on free non-renewable resources, supply chains risk over-exploitation of such critical resources (e.g., groundwater), which may impact their ability to access them (Alkhuzaim et al., 2021; López-Gamero, Molina-Azorin, et al., 2011).

From an emergy perspective, a high EYR ratio indicates significant ecological contribution to a supply chain's operational sustainability (Guo et al., 2023). The walnut shell by-product supply chain's higher EYR does not support Hypothesis 4, which states: *"Because of better exploitation of local resources, the ecological impact on the walnut shell by-product supply chain is higher than that on the date seed by-product supply chain."* In other words, the walnut shell by-product supply chain's higher EYR value indicates that it exploits local resources more efficiently than the date seed by-product supply chain. This conclusion is corroborated by Zhang et al. (2007), who used EYR (among other indicators) to evaluate multiple cropping-grazing systems; they found that the system with the highest EYR used local resources most efficiently. In light of this finding, we posit that the walnut shell by-product supply chain's more efficient exploitation of local resources indicates that, compared to the date seed by-product supply chain, it is less dependent on the natural environment and faces a lower ecological impact.

The EIR results do not support Hypothesis 5, which states: *"Because of a high utilization level of local natural resources, date seed by-product supply chain is less dependent on the natural environment than the walnut shell by-product supply chain."*

The results suggest that the walnut shell by-product supply chain has a higher utilization level of local natural resources than the date seed by-product supply chain. The EIR also indicates that the walnut shell by-product supply chain is less dependent on the natural environment, and hence has a lower ecological impact than the date seed by-product supply chain.

Based on the reported results and the tested hypotheses, we can synthesize the first proposition as follows:

Proposition 1: Various emergy indicators can be utilized to improve and support various supply chain decisions and actions.

This research uses four emergy indicators (i.e., EYR, ESI, ELR, and EIR); however, the literature provides various indicators that evaluate systems from multiple dimensions (Brown and Ulgiati, 2004; Odum, 1996; Wang et al., 2022).

Highlighting the variations between the unit emergy values (UEV) of each supply chain and the emergy suggests that in a multi-tier circular supply chain, certain activities may influence the overall performance of an extended supply chain. Results also suggest that excluding tiers with high consumption of natural resources may produce different results and highlight different aspects of the circularity of a supply chain. Thus, the second proposition is developed as follows:

Proposition 2: In a multi-tiered supply chain, the performance of individual tiers with high consumption of natural resources can have a great influence on the overall performance from an emergy perspective.

7.3.2 Use of Emergy Indicators as Scales for the Natural Resource Dependence Theory

So far, we have presented the results of the NRDT-derived hypotheses, and there are also insights within the larger research question as to how emergy can be used for evaluating NRDT and circular supply chains. Very few previous studies have incorporated the NRDT as a theoretical lens to evaluate or understand organizational and supply chain decisions, and no study has developed a sound, practical index or scale capable of empirically measuring relationships or NRDT constructs.

For instance, building on Tashman (2011) extension of the RDT, Bergmann et al. (2016) conducted a qualitative comparative analysis to evaluate the impact of extreme weather conditions on financial performance based on the NRDT. Their study conducted 38 interviews with small and medium enterprises (SMEs) across various industries. Despite the use of NRDT as a theoretical foundation for the applied analyses, their study does not provide a quantitative measure for NRDT in relation to organizational decisions. Similarly, Craig and Ma (2022) used statistical analysis to empirically investigate the impact of weather on organizations' financial performance within the tourism industry. Furthermore, some studies have used NRDT as a conceptual framework to explain certain organizational contexts (Dias et al., 2022; Figge and Hahn, 2021; Tashman, 2021). Most of these studies employed NRDT to investigate the impact of climate change and extreme weather on organizational performance; however, none were conducted at the supply chain level adopting a donor-side approach with clear objective scale measures for NRDT.

In general, this research offers a theoretical foundation by developing measurable indices to quantify NRDT constructs from a donor-side perspective. It also exemplifies the application and insights—via hypotheses testing—of the application of EA to evaluate NRDT constructs. Emergy prioritizes the contribution of ecological services as a core construct of the theory. By doing so, this dissertation makes a substantive theoretical contribution to the field of supply chain management and circular economy investigation. Based on the discussion thus far, two research propositions follow:

Proposition 3: The ecological impact on organizations in general and supply chains in particular can be quantitatively measured from a donor-side approach using the emergy yield ratio indicator and the emergy investment ratio. These measures can prove valuable for advancing understanding of NRDT for circular supply chain outcomes.

Proposition 4: The organizational and supply chain impact on the natural system can be quantitatively measured using the emergy loading ratio and the emergy sustainability index indicators.

7.3.3 Policy Implications, Evaluation of NRDT Hypotheses Using Emergy Systems Dynamics

The emergy SD model improves our understanding of the implications of external shocks to NRDT results. In this case, dynamic multidimensional relationships between organizations and their operating environment are investigated using a "dynamic NRDT" perspective. The model investigates the impact of policy interventions on the emergy results of the date cultivation stage of the date seed by-product supply chain in particular, excluding the remaining phases of transporting and processing the date seed by-products.

The SD model results show that the EA of the date seed by-product supply chain can be significantly improved via policy interventions. These improvements are illustrated using ELR and *%N* over time as emergy indicators to track the supply chain's dynamic behavior. At a different level of analysis, Song et al. (2014) used ELR to test the effectiveness of certain environmental protection policies in improving the performance of an urban metabolic system using SD. They found that environmental protection policies helped reduce environmental pressure over time.

Similar to the emergy evaluation, NRDT can be employed as a theoretical foundation for the SD model's behavior. In this analysis, *%N* is used as an indicator for a government subsidy policy to regulate agriculture-related practices stemming from Saudi Arabia's Vision 2030, which is supported by Agricultural Development Fund (2019) initiatives that subsidize sustainable agricultural practices. This policy influences one element of the NRDT concerning the impact of the natural system on organizations and any related dependencies. In particular, the higher the *%N*, the higher dependency on natural resources—and, thus, the greater the impact of the natural system on organizations (Table 7-3). Furthermore, these dependencies are caused by the system's reliance on a critical natural resource: groundwater.

Simulation results of the emergy SD model (see Sections 6.8 and 7.2 and Table 7-3) suggest that government subsidy can play a major role in reducing the impact of natural resource scarcity on the date seed by-product supply chain, based on changes in non-renewable resource consumption (*%N*). From an NRDT perspective, this observation indicates that the impact of organizational dependency on the natural system is mitigated.

The emergy SD model provides a method to verify Hypotheses 6 and 7, which focus on the impact of policy interventions from the NRDT perspective. Hypothesis 6 states: *"The percentage of non-renewable resources used in the date supply chain is lower due to the impact of a government subsidy policy."* It can be inferred from the *%N* values that Hypothesis 6 has sufficient support; *%N* is reduced as a result of government subsidies seeking to promote the adoption of drip irrigation systems. This finding is corroborated by a number of prior studies that investigated the impact of agriculture subsidies on irrigation systems in reducing the consumption of groundwater in Saudi Arabia (Abderrahman, 2001; Grindle et al., 2015; Ouda, 2014). Relating this result to the NRDT construct, the *%N* indicator represents a scale measure for the natural non-renewable resource dependence of organizations or their supply chains. According to the simulation results of the second scenario (see Section 7.2), dependence on the natural environment (i.e., groundwater) is reduced as a result the government subsidy policy (P1). This result also indicates that the organization's ecological impact is lessened. The main objective of P1 is to reduce the consumption of groundwater, which is a scarce non-renewable resource in Saudi Arabia.

In addition, the ELR emergy indicator is used to evaluate the second policy (P2), which controls environmental concerns about the system's operations. The ELR indicator depicts another NRDT theoretical construct that emphasizes the impact of the date seed by-product supply chain on the natural system (especially the groundwater). The policy aims to control changes in the cultivated area by tracking ELR behavior over time and is based on a similar Saudi government policy that seeks to curb water use by suspending wheat and fodder cultivation (Ministry of Environment Water and Agriculture, 2018a; Royal Decree No. M/66, 2015).

In general, SD has been used to examine the effect of government subsidy policies on the development of environmentally sustainable practices across multiple levels of analysis. For instance, SD modeling has been employed to investigate the impact of subsidy policies at the urban level (Li et al., 2020; Ye et al., 2021), industry level (Eker and Van Daalen, 2015; Hsu, 2012; Kuo et al., 2019; Wang et al., 2021), and supply chain level (Li et al., 2020; Y. Liu et al., 2018; Preisler et al., 2013; Tian et al., 2014). With relation to irrigation and water management techniques as well as the adoption of sustainable practices within agriculture, a number of studies have used SD to emphasize the role of government subsidy in enhancing water management practices and promoting the adoption of modern irrigation techniques (Cremades et al., 2015; Pluchinotta et al., 2018; Tian et al., 2014). The impact of environmental protection policies concerning natural resource consumption has also been investigated using SD modeling, with findings that indicate the positive impact of such policies on improving utilization of natural resources (Li et al., 2012; Zhang et al., 2014).

As for the second policy (P2) (Chapter 6, Section 6.6), ELR is used to control environmental concerns about the system's operations during the expansion of date cultivated area, which depicts the other theoretical element of the NRDT that emphasizes the impact of the date supply chain on the natural system. The policy aims to control changes in the cultivated area by tracking ELR behavior over time. Within the same perspective, a study by Naderi et al. (2021) used SD to test several policies, including the management of cultivated area to reduce water stress caused by agricultural activities. The researchers found that reducing the cultivated area results in a decline in water consumption.

Simulation results from Sections 6.8 and 7.2 reveal the effectiveness of this policy in improving the supply chain's emergy performance by reducing its environmental burden (ELR). ELR is also used to test Hypothesis 7, which states: *"The environmental pressure is reduced as a result of Saudi Arabia's regulatory environmental actions."* This hypothesis is supported by the results of the emergy SD model through the values of the ELR. Positive outcomes were observed once regulatory actions related to environmental concerns (P2) were implemented. This policy reduced the environmental pressure caused by date cultivation operations by 50%. Moreover, from the NRDT perspective, ELR improvement via the implemented policy indicates a lower organizational impact on the natural environment.

Although results of the SD model simulations indicated the individual effectiveness of P1 and P2, simultaneously implementing these two policies generated the best performance for the date seed by-product supply chain. P1 represents a fiscal policy wherein the government provides subsidies for certain agricultural equipment (e.g., irrigation systems) (Akbar and Jamil, 2012). P2, on the other hand, is a policy control instrument for natural resources and environmental protection (Hardaker, 1997). In this research, the results summarized in Table 7-3 indicate that the implementation of fiscal policies (i.e., subsidies) simultaneously with environmental protection control instruments (i.e., cultivated land control) can have a synergistic effect on the system's performance (Hardaker, 1997).

7.3.4 Insights from Both the Emergy Analysis and Emergy Systems Dynamics Results

For both of the by-product supply chains under study, the cultivation phase is the greatest contributor to overall performance, as evidenced by the results of the emergy evaluations summarized in Section 7.1, Table 7-1. Observations from both the EA and the emergy SD results provide a number of insights (see Sections 7.1 and 7.2). The emergy SD model showed that policy interventions contributed positively to not only the modeled date cultivation system but also the emergy performance of the entire date seed by-product supply chain.

The emergy-based indicators of the multitier date seed by-product supply chain were re-calculated and compared to the basic walnut shell by-product supply chain to investigate the feasibility of implemented policies; these results are presented in Table 7-4. This investigation is based on a study conducted by Seles et al. (2016), which indicates that in a multitier supply chain, environmental pressures exerted by the government are transmitted up and down a supply chain, from one tier to the next, stimulating the adoption of sustainable practices. Thus, the extensive application of quantitative analysis employed in this research has shown that the impact of government policies can also be transmitted across the supply chain.

The EA of the date seed by-product supply chain results yield additional insights. According to Odum (1996), emergy is an accumulation of energy transformations that have contributed directly and indirectly to produce a product or a service—in our study the date seed by-products. As a result, the energy transformations that were carried out from the point of producing dates up to the point of producing the date seed by-products are all accounted for, including all inputs and flows to the system (Le Corre, 2016). Based on the results of both evaluations, we found that in a CE context, the implications of the implemented policies are readily apparent across all tiers of the by-product supply chain, even though these policies are broad in scope and centered on a natural resource dependence perspective. Based on that, a fifth proposition is synthesized as follows:

Proposition 5: In an emergy-based circular supply chain system, and from the theoretical perspective of NRDT, the implications of governmental policies can be transmitted across a multitier supply chain that influences the two-way relationships between the supply chain and the natural environment.

With consideration to some key differences in the scope of this research, similar published studies integrating policy interventions using a coupled SD and EA approach exist. SD and EA have been used mostly within a much broader level compared to this study. For instance, SD has been integrated as a policy testing tool evaluating emergy systems in an urban metabolic level (Fang et al., 2017; Huang et al., 2018; Huo et al., 2022; Liu et al., 2014; Song et al., 2014; Xue et al., 2018), industrial park level (Zhao et al., 2022), and industry level (Ekinci et al., 2020; Liu et al., 2014; Wu et al., 2021). The focus of these published studies is primarily at a macroscopic level, testing the impact of various policies through tracking the emergy indicators over time. A variety of emergy indicators were used, measuring the performance of each system from a different respective. For instance, Fang et al. (2017) simulated the ecological and economic system of Beijing under different policies, using the percentage of non-renewable emergy of the total emergy, total imported emergy, and ratio of exported emergy. Similar to the emergy indicators used in this dissertation thesis, Wu et al. (2021) conducted an emergy evaluation using SD for the transportation industry in China. They used ELR, ESI, and EYR to track the behavior of the SD model under policy intervention scenarios.

The results shown in Table 7-3 provide some interesting insights about the impact of policy interactions in the context of supply chains in general. Most notably, SD model testing showed that simultaneously implementing the two policies (P1 and P2) generated the best performance of the date seed by-product supply chain under study; the impact of such synergistic policy implementation may have broader implications (Hardaker, 1997). Thus, a sixth proposition is synthesized:

Proposition 6: Simultaneous policies can have synergistic effects on outcomes.

Research coupling EA with SD is limited, especially at the organizational and supply chain levels using the NRDT lens. This study narrows that research gap by integrating operational and theoretical elements using EA and emergy SD methodologies to explore a new avenue of research, employing an integrative emergy SD approach and an emergent theoretical perspective to investigate CE supply chains.

7.4 Practical Implications

The results of this research exemplify practical integration of emergy and SD. EA is used to evaluate two CE supply chains that produce two by-products used in Saudi Aramco drilling operations, and the results obtained by emergy evaluation may be used to inform Aramco's sourcing decisions for such materials. The results indicate that even though Aramco's well operations are conducted locally, using locally available date seed by-products is not an environmentally rational sourcing decision from a donor-side perspective. In essence, this is because the cultivation of dates—the primary source of the by-product used in Aramco's drilling operations—involves farming practices that impose a tremendous environmental burden, which is compounded at every subsequent phase of the supply chain.

In terms of SD use, although the presented model focuses solely on date cultivation, its results offer some potentially useful policy solutions for agricultural reform. The tested policies aim to control the cultivated area and use of groundwater as a non-renewable resource, which affects the aggregate emergy performance of the entire supply chain. The integrative emergy SD approach drew a roadmap for improving the performance of the date seed by-product supply chain, providing solid scientific grounds for Aramco's user-side organizational (supply chain) decision to replace walnut shell by-products with date seed by-products. The tools can be used by policymakers to adjust and integrate policies that seek to reduce environmental burdens and limit the environmental dependence of organizations and industries in countries with scarce natural resources.

7.5 What Are the Answers to the Overall Research Questions?

The results of the integrated methodologies offered some answers to the proposed research questions. The first research question is: *Can emergy analysis aid theoretical and practical environmental assessment at the supply chain level within a CE context?* The answer is: *Yes, EA can be applied successfully at a CE supply chain level while offering some theoretical and practical implications.* The answer stems from conducting EA on the respective supply chains of date seed and walnut shell by-products, using Aramco as a case study, after which their emergy-based indicators are calculated and analyzed. The results indicate that the walnut shell by-products supply chain has a better emergy performance compared to the local supply chain of date seed by-products.

The calculated emergy-based indicators (ELR, EYR, EIR, and ESI) reveal that importing walnut shells from the US is the more sustainable sourcing decision when considering the energy memory (emergy) of all constructing resources, energy flow, and human services. From a theoretical perspective, EA forms a solid association with NRDT by providing a measurable index for the theory's main elements. The application of NRDT within a CE supply chain setting helps to contextualize a donor-side perspective for an organization's relationship with its surrounding natural system.

However, difficulties did arise, which imposed some limitations on the analyses performed in this research. One major limitation was the unavailability of raw data concerning the supply chains under study. A series of assumptions were made to overcome this limitation, but the lack of such data may nevertheless degrade the accuracy of the reported results. Another major limitation was the scarcity of literature pertaining to both the scope and characteristic of this study, which posed challenges for the emergy evaluations and SD modeling approaches.

The second research question is: *How does government policy play a role in natural resource dependency (organizational decisions) in a supply chain by-product (CE) setting?* The answer (*Yes*) is provided by the emergy SD model of date cultivation. In building the SD model and constructing the resources used to cultivate dates, a number of assumptions can be made regarding the role of natural resource dependency in a supply chain by-product (CE) setting. One of the two government policies tested here aimed to control applications of modern irrigation methods, while the other aimed to control the area used to cultivate date palm trees. The main purpose of both policies was to control the date production industry's dependency on groundwater, which is a scarce resource in Saudi Arabia. Thus, natural resource dependency is regulated via policy interventions, thereby mitigating risks associated with organizational ecosystem dependence. In answering the second research question, links are built between emergy and SD as a methodology applicable to the setting of CE supply chains and the management of natural resource dependencies using government policies.

The next (and final) chapter, Chapter 8, concludes this dissertation thesis by summarizing the main findings of the joint emergy SD approach used to evaluate the respective supply chains of date seed and walnut shell by-products. Additionally, potential avenues for future research will be presented in light of this study's results and limitations.

CHAPTER 8 : CONCLUSION AND FUTURE DIRECTIONS

This chapter concludes the dissertation thesis by summarizing research implications, recognizing limitations, and proposing directions for future studies.

The emergy analysis (EA) results specifically suggest that the performance of the walnut shell by-product supply chain is more sustainable than that of the date seed by-product supply chain, although the latter was more localized—indeed, it was on this basis that an argument was made in its favor as a more sustainable solution. The emergy-based indicators show that cultivating dates (the first phase in the supply chain of the date seed by-product under study) imposes a higher environmental burden than walnut production. Thus, the results of the emergy evaluation did not provide sufficient support for Hypotheses 1 through 5, which stipulated that the date seed by-product supply chain would perform better on various sustainability characteristics that were informed by NRDT. Broadly, these results show how EA can support insight for evaluating alternative supply chains—especially with CE practices—for organizations, managers, and other stakeholders.

In addition to EA, an emergy-based SD model was constructed using Stella Architect software to present the emergy system of date cultivation. This SD model simulated four scenarios to investigate the impact of two government policies in the emergy evaluation of date cultivation. The model used two emergy indicators, ELR and *N%*, to track the date seed supply chain's environmental behavior over a period of 25 years. The four scenarios included: 1) the baseline scenario, wherein both flood and drip irrigation systems are adopted equally; 2) implementing the government subsidy policy (P1) (Chapter 6, Section 6.7); 3) implementing the environmental pressure policy (P2) (Chapter 6, Section 6.7); and 4) integrating the government subsidy policy

(P1) with the environmental pressure policy (P2). The simulation results of the emergy SD model revealed that integrating the two proposed policies produced the best emergy performance through improving the emergy-based indicators over time, thus providing sufficient support for Hypotheses 6 and 7.

Two major research questions were posited in the initial stages of this dissertation (Chapter 3, Section 3.4). The first (R1) was: *Can emergy analysis aid theoretical and practical environmental assessment at the supply chain level within a CE context?* The second (R2) was: *How does government policy play a role in natural resource dependency (organizational decisions) in a supply chain by-product (CE) setting?*

Each methodology provides insight into the research questions. From an NRDT perspective, the first question is answered by conducting EA along the date seed by-product and walnut shell by-product supply chains, illustrating a CE setting in both. Results indicated that EA can aid theoretical and practical environmental assessment at the supply chain level within a CE setting. The second question, which focuses on the role of broader policy in a supply chain by-product setting, is addressed using emergy-based SD modeling to explore potential political reforms to improve the supply chain’s emergy performance. The results of the SD model indicated the viability of proposed policy interventions for environmentally sustainable development of the date industry in general. This result has a positive ripple effect that enhances the performance of the entire date seed by-product supply chain. That is, policy interventions can improve organizations’ and supply chains’ resource dependence on the natural environment—as well as organizations’ and supply chains’ impacts on the natural environment.

8.1 Contributions

This dissertation thesis contributes to the current literature by developing and applying a multidisciplinary integrative approach that incorporates EA and SD with an organizational theory at the supply chain level, while following a natural resource dependence perspective. The integrative perspective shows analytical, environmental, policy, and organizational and supply chain integration. The research also provides some significant practical and theoretical contributions.

According to the results of the emergy evaluations, the date seed by-product supply chain is not necessarily a more sustainable alternative to the walnut shell by-product supply chain. Nevertheless, there are opportunities to improve some of its processes. For instance, date cultivation practices create the greatest environmental pressure, which affects the supply chain’s emergy performance. One of the opportunities for improvement is the reduction of groundwater consumption of groundwater—not only through the use of modern irrigation techniques such as drip irrigation, but also by promoting the use of treated wastewater, which is one of the strategic goals of the KSA National Vision 2030 (Ministry of Environment Water and Agriculture, 2018a).

From a practical perspective, this dissertation thesis aligns with recent Saudi initiatives concerning the implementations of CE practices. For instance, Saudi Aramco’s presence in the local market gives the company a prime position to lead the way in implementing CE practices, thereby supporting some sustainability and economic development efforts. Accordingly, in 2015, Saudi Aramco launched the In Kingdom Saudi Value Add (IKTVA) program, which focuses on local suppliers aspiring to maximize value creation along the supply chain. For this reason, as one of the first studies conducted at a supply chain granularity level within a CE setting, this dissertation thesis offers a comprehensive measuring tool that can become part of the organizational decision-making process.

This dissertation thesis constitutes the first extensive evaluation employing a joint methodological approach based on EA and SD, both conceptualized through the NRDT's perspective, at the supply chain level within a CE context. The use of the case study reflects realistic supply chain challenges and critical organizational decisions. EA provides a foundation for developing measurement scales for NRDT constructs. Specifically, the emergy yield ratio (EYR) and the emergy investment ratio (EIR) are used to measure the ecological impact on organizations in general and supply chains in particular. These measures are also valuable in assessing the degree of dependence on natural resources. The emergy loading ratio (ELR) and emergy sustainable index (ESI) are used to measure the organizational impact on the natural environment.

The main contributions of this dissertation are: (1) advancing the practical use of performance measures in general, and environmental performance measures in particular, for sustainable supply chain management (SSCM) practices; (2) expanding the practical applications of emergy analysis (EA) within the supply chain level with greater focus on supply chain-related decisions; (3) expanding and linking organizational theory to EA by testing elements of the natural resource dependence theory (NRDT) using the presented joint methodology; and (4) using system dynamics (SD) modeling as a policymaking tool to aid in supply chain-related decisions.

8.2 Study Limitations

Although this study offers many contributions and insights, some of these are tempered by significant limitations that must be acknowledged. The application of EA is inherently more applicable to broad levels of analysis, such as the national, urban, industrial park, and industry levels. In other words, the underdeveloped literature incorporating EA at a granular level poses a challenge by hindering the potential expansion of emergy evaluations at the microscopic (i.e., organizational and supply chain) levels. As a result, the application of emergy analysis at a supply chain level in this thesis was confronted by uncertainties regarding the UEV values involved in constructing components of the final product.

Based on the reported results and the differences between the values of the unit emergy value (UEV) and the emergy indicators (i.e., ELR, EYR, ESI, and EIR), some limitations are identified. Although accounting for all the direct and indirect energy is a core role in EA, the inability of emergy evaluations to capture the variations between a global and local supply chain raised an issue of inconsistent grounds for comparisons within a supply chain level. In other words, the results were tilted in favor of the walnut shell by-product supply chain because of the inclusion of the cultivation of the dates and walnuts in the study. Excluding cultivation activities from the emergy evaluations would provide radically different results. This suggests a general limitation with using emergy at a circular supply chain context, which requires further investigation.

Another important issue is whether processing the date seed as a by-product produces a higher environmental impact as opposed to disposing of the date seed as waste generated from the date paste transformative factories in Saudi Arabia. For instance, according to emergy, if the energy has no potential to do work (i.e., produce a product or a service), its emergy is zero (Odum, 1996); thus, if disposing of the date seed is the more environmentally conscious option, reusing the date seed as a by-product may not be viable from a sustainability perspective. This adds another limitation of applying emergy within a circular economy supply chain as emergy considers only systems that have potential to produce work.

One of the greatest limitations in this emergy evaluation was the unavailability of real supply chain-related data. Because this emergy evaluation covers expanded multitier supply chains, it was extremely difficult to trace data for all inputs and resources. Thus, secondary data sources were used to account for many undetermined inputs. In addition, historical data was utilized to estimate data regarding some natural and industrial resources; such data is subject to significant variation over time.

Furthermore, this research used a single case study to apply the proposed integrative emergy SD approach; thus, further investigation and revision may be necessary to ensure the feasibility of such an approach within a CE supply chain context (Rodrigues et al., 2021).

Although the proposed emergy SD model provides an experimental environment to simulate real-world scenarios, a number of limitations may impact the model's applicability to similar production systems. The main limitation is inherent to emergy as a methodology, which affects the ability to replicate EA for SD modeling in terms of tracing supply chain-related activities. Moreover, the lack of an integrated analysis conducting EA and SA in the same studied context made it difficult to validate the model's structure with reference to historical applications from the literature. It was difficult to validate the model due to a lack of access to various experts in the field; the development of SD models requires various mental models as well as the gathering of detailed information and validation from numerous experts. The confidential nature of the processes (i.e., protected intellectual property) precluded access to primary sources of particular information (e.g., validation of the SD model from experts and other direct sources). The intended purpose of some policies was based on archival information; actual policy experts who were involved with or managed these policies might provide nuanced information that would alter some relationships in the designed model. Further investigation is required to refine the accuracy of these models.

Another drawback of the evaluated system was the absence of a comprehensive national emergy database; it was necessary to make numerous assumptions from the broader emergy database to arrive at specific supply chain characteristics. Finally, the integration of EA with SD remains an emerging topic of study that calls for further exploration at the supply chain level, in terms of accuracy and validity.

8.3 Future Research

In light of the stated results and limitations, we can propose a number of promising avenues for future research into the context of EA at the supply chain level.

To expand upon the current study, further exploration of date production performance in Saudi Arabia may incorporate important aspects of the date industry that were not considered in this dissertation study, such as the impact of local and international demand on date production and its effect on groundwater consumption. Instead of increasing production beyond local self-sufficiency at the risk of further depleting groundwater resources, more sustainable approaches to production growth must be sought. On the other hand, for Aramco's supply chain, changes in date production will affect the availability of date seeds (and, ultimately, date seed by-products) in the local market. If the demand for dates were to decrease, and assuming that date production must be reduced to a certain level, the date waste (i.e., date seeds) would also be reduced, which would ultimately impact the production of lost circulation materials used in drilling.

One of the most daunting challenges confronting the Saudi government is the implementation of effective water management strategies. Thus, there is substantial impetus for research that seeks a balance between the Saudi government's attempts to conserve scarce non-renewable water resources while meeting diversification goals by increasing date exports. To mitigate current water scarcity issues, a joint emergy SD approach can be employed to analyze various water management strategies, such as by evaluating the use of wastewater for agricultural use. Furthermore, a replication of the proposed emergy SD model may help inform the decision-making processes that underlie water preservation policies in Saudi Arabia by investigating several scenarios and expanding the current work to a broader level of analysis.

Another potentially fruitful area of research would evaluate the waste management techniques applied to date seeds as agricultural waste, comparing the respective emergies entailed by disposing of date seeds versus reusing them as a by-product with commercial applications (similar to lost circulation materials). The research question for such an investigation might be something like: *Is the emergy performance of disposing of date seeds better than that of remanufacturing them for a value-adding process?*

Additionally, further studies that support this research with data specific to the evaluated supply chains (i.e., date seed and walnut shell by-products) will enhance the accuracy of the analyses conducted herein. By utilizing real data, many potential research areas can be explored, offering a practical organizational tool for environmental performance assessments, such as investigating whether variations exist within supply chain management results (decisions/choices) based on EA versus traditional business measures (cost) within the SSCM context.

Shifting our attention to SD, we might also propose a more comprehensive analysis of the emergy SD model to investigate the effect of other potential policies. For instance, a future study may test the effect of trade agreements on the performance of date seed and walnut shell by-product supply chains, considering that walnut shell by-products are imported—whereas date seed by-products are locally available and thus exempt from trade agreements. Such a policy focuses on the economic aspect of the date industry. Currently, Aramco is locally procuring and manufacturing date waste for conversion into lost circulation materials. The policy focuses on the impact of trade facilitations for importing date waste from non-local sources on the emergy performance of the supply chain.

Pursuant to the 2030 Saudi Vision objective of diversifying the local economy, the Saudi government is trying to attract investments in unrelated oil projects. Environmentally oriented projects (e.g., CE) are an example of such anticipated investments. Now that Saudi Aramco is listed for public trading on the Saudi Stock Exchange, more investments will be directed into the local market. The idea of polarizing foreign investments puts greater pressure on the local market to advance sustainable development practices. By adopting a circular supply chain with regard to date seed by-products, Aramco is more likely to attract such investments.

EA provides a number of additional ratios and measures; it remains to be seen whether these can be related to other organizational and policy theories. NRDT was a starting point of organizational theory that may be investigated using EA. Other theoretical perspectives—such as ecological modernization theory, institutional theory, and transaction cost theory—may also be evaluated using emergy metrics. Further studies might investigate the integration of these theories and test them with various methodologies introduced in this dissertation.

8.4 Conclusion

Based on an environmentally oriented theoretical foundation, this thesis aimed to extend the applications of inherently broad environmentally integrative performance measures at a supply chain CE level. It contributes a comprehensive measuring tool to help inform the organizational decision-making process. We have completed extensive investigations along two CE supply chains using a joint emergy SD approach that incorporates a natural dependence theory perspective. As a proof-of-concept, our case study evaluation focuses on Saudi Aramco's supply chain processes to conduct the integrative methodology.

EA is used to evaluate two multi-tiered CE supply chains, namely those of date seed and walnut shell by-products. In addition to EA, an SD model was constructed using Stella Architect software. The model presented the emergy system of date cultivation, which is the first (and most environmentally impactful) phase of the date seed by-product supply chain. The SD model is used as a policy intervention tool by simulating four scenarios to investigate the impact of two government policies on the emergy evaluation of date cultivation.

This research seeks to address the lack of a theory-driven approach, the limited application of EA at an organizational level, and the impact of government policy in a CE supply chain setting. By filling these gaps, this dissertation thesis provides a theoretically based approach to help supply chain scholars and practitioners plan scientifically designed supply chain mitigation strategies. Therefore, in theoretical terms, we have shown how external shocks (i.e., government policies) can play a decisive role in the natural resource dependence of various by-products within circular activities for supply chains (by-products usage). In methodological terms, we have demonstrated how emergy and SD can be applied at the supply chain level, even to specific by-products. Finally, we have shown that further integration of SD and emergy measures is feasible and indeed may be necessary for effective evaluation of dynamic complex systems.

This work paves the way for further research explorations into the context of EA at the supply chain level. Opportunities for further investigation exist in addressing the many theoretical gaps that prevent the efficient application of emergy to supply chain management and circularity research.

APPENDICES

Appendix A: List of Acronyms

Acronym	Definition
EA	Emergy Analysis
SCM	Supply Chain Management
SSCM	Sustainable Supply Chain Management
CE	Circular Economy
CSCMP	Council of Supply Chain Management Professionals
SCOR	Supply Chain Operations Reference
LCCA	Life Cycle Costing Assessment
SD	System Dynamics
CLD	Causal Loop diagram
RDT	Resource Dependence Theory
NRDT	Natural Resource Dependence Theory
RBV	Resource-Based View
NRBV	Natural Resource-Based View
LCA	Life Cycle Assessment
NEAD	National Environmental Accounting Database
UEV	Unit Emergy Value
R	Renewable Resources
N	Non-renewable Resources
IM	Purchased Resources
L	Labor
S	Services
U	Total Emergy
Y	Yield
ELR	Emergy Loading Ratio
EYR	Emergy Yield Ratio
ESI	Emergy Sustainability Index
EIR	Emergy Investment ratio
%N	Percent Non-Renewable
GHG	Greenhouse Gas
sej	solar emergy joules

J	Joule
g	gram
Yr	Year
hr	Hour
kWh	Kilowatt-hour

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