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Review

Systems Thinking for Planning Sustainable Desert Agriculture Systems with Saline Groundwater Irrigation: A Review

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Abstract: Agricultural land expansion is a solution to address global food security challenges in the context of climate change. However, the sustainability of expansion in arid countries is difficult because of scarce surface water resources, groundwater salinity, and the health of salt-affected soil. Developing expansion and sustainability plans for agriculture requires systems thinking, considering the complex feedback interactions between saline groundwater, salt-affected soil, plant growth, fresh-water mixing with saline groundwater, irrigation systems, and the application of soil amendments to alleviate the salinity impacts. This study presents an extensive literature review on the effects of salinity on soil and plant health, the constraints and opportunities for sustainable agriculture in Egypt, and a systems thinking approach to the feedback interactions between saline water, salt-affected soil, and the application of soil amendments to achieve required crop yields. Insights and strategies are discussed, including a system-dynamics-based decision model, irrigation systems with diversified and decentralized water sources, urban water demand management, energy availability, smart irrigation systems, and active participation of stakeholders to achieve sustainable agriculture under climate and socioeconomic changes. The insights are expected to encourage stakeholders and academic communities in the water, agriculture, and related food security sectors to develop a quantitative and systematic decision-making framework for sustainable agriculture systems in arid regions.

Keywords: systems thinking; desert agriculture; food security; salinity; soil amendment; groundwater; climate change

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1. Introduction

Food security is a global cross-sectoral challenge that will persist for the coming decades [1]. The projections of the global population increasing past nine billion people will drive the demand for food beyond local resource availability and system capacities [2]. Reductions in the amount and the productivity of agricultural land, falling crop yields, the dearth of research and development funds, increasing water competition and scarcity, and declining investments in agriculture infrastructure combined with growing demand for food are accelerating the challenge [1,3,4]. Reductions in water availability and increased intensification of extremely dry conditions further the challenge [5–7]. These interconnections across the water and food nexus lead to a self-reinforcing decline of available resources needed to sustain food production and, more broadly, sustainable communities and global economic activities [8].

Food security is a more difficult challenge for developing nations. Rapid population growth, dwindling arable land, and constraints on water supply, quality, and distribution infrastructure have all contributed to unsustainable and inflexible food production systems [9]. In addition, poverty and a general lack of effective governance and policy-making capacities constrain developing nations from planning, designing, and implementing practical long-term strategies to address issues with food security [10].

All nations seek to address their collection of factors driving inadequate food production that leads to food insecurity. This search for solutions has led to investigating the expansion of agricultural systems into lands not previously considered for crop production but having potential when developed in specific ways [11]. One of these solutions that have been demonstrated successfully in the Western United States is reclaiming drylands and desert lands [12]. This has emerged as a potentially feasible idea in the Middle East and North Africa in particular [11].

In Egypt, there is a high priority to enhance agricultural production as a pillar of national food security [13]. The country is one of many turning to the reclamation of desert lands to meet this need and the use of local groundwater sources for irrigation [11,14,15]. One aim of this review paper is to provide valuable insights into the challenges and opportunities for agricultural production—especially that of wheat—in Egypt. Egypt faces multiple changes—some specific to its context, and others that are common challenges for those moving into new agricultural lands. With a population of 102 million in 2020 and annual population growth of about 2%, Egypt is regarded as one of the fastest-growing countries in the African continent [16]. Per the current growth rate, the projected population of Egypt by 2050 is estimated at 190 million [17]. Egypt's total land area is 1,000,450 km^2, of which around 95% is uninhabited or desert land [18]. The agriculture sector of Egypt is a significant component of the Egyptian economy, contributing 14.5% of the country's gross domestic product [19]. The agricultural sector accounts for 25% of all jobs [20], and over 55% of employment in Upper Egypt is agriculture-related [21]. Egypt's agriculture sector is dominated by small farms using traditional practices. Field crops contribute about 75% of the total value of Egypt's agricultural production, while the rest comes from livestock products, fruits and vegetables, and other specialty crops. Major field crops include corn (maize), rice, wheat, sorghum, and fava (broad) beans [22]. Egypt relies primarily on the Nile River for its water supply [23,24], and its 3.3 million hectares of agricultural land consumes more than 85% of the water withdrawals [25].

Despite a considerable output, cereal production in Egypt falls short of the country's total consumption. A substantial amount of foreign exchange is spent annually on importing cereals and milling products [26]. Egypt is one of the major wheat producers in Africa, with 8.4 million tons in 2013 against its consumption of 18.49 million tons [27]. However, Egypt was the largest wheat importer in the world in 2020 [28]. One of the main challenges of wheat production in Egypt is the insufficient available land area. The total arable area is 3.3 million hectares, which is mainly located in the Nile Valley and Delta. This land is highly fertile and productive and can be cropped twice or even three times per year. Most land is cropped at least twice per year, but agricultural productivity is limited by several environmental stresses, such as salinity and drought. Salinity afflicts an estimated 35% of cultivated land due to drainage problems and progressive saline irrigation [29–31]. Another challenge to Egypt's agriculture is a shortage of fresh water. Egypt is located in an arid to semi-arid zone [32]. Water is a scarce resource in the region, with the major source of this essential commodity being the Nile River. The second and most imminent threat is the growth of the population, which can lower the per capita water availability [33]. By

2050, Africa's population is expected to grow by an additional 1.3 billion— the equivalent of today's China. The current objective for Egypt is to look for perennial solutions to reduce its dependency on the Nile water supply and find sustainable alternatives to ensure food security for its population.

Assessing the practicability of alternative strategies to expand agriculture sustainably in desert regions, particularly with the irrigation of saline groundwater, raises numerous questions regarding the salinity and quality of the local water sources, the improvement of soil conditions with amendments, population dynamics, and social adjustments, to name a few. To illustrate the complex interconnections across water sources, water use, crop types, weather and climate, soil characteristics, energy needs, labor needs, etc., the assessment needs to take a systems approach.

This paper aims to (1) present a review of the literature spotlighting the key system components that need to be considered to overcome the salinity of local groundwater used for irrigation of reclaimed desert lands, and (2) synthesize pertinent information, recommendations for system-dynamics-based analysis, and ideas for systems-level solutions. Focal areas summarized in this review include the salinity effects on crop production in Egyptian/reclaimed desert land (arid and semi-arid regions); the use of soil amendments and water mixing to mitigate the salinity effects; and approaches based on systems thinking and system dynamics modeling to study the complex system and evaluate sustainability solutions. The paper also aims to (3) emphasize the need for a systems approach for sustainable desert agricultural systems across the sectors of water, agriculture, economics, society, types of farms (subsistence vs. commercial), cultural influences, public health, the area under cultivation (mostly smaller farms that influence the economic feasibility), policies that limit flexibility, population growth, and climate change dynamics/population migration. Thus, we critically discuss the challenges and opportunities with systems thinking to analyze the reclamation of agricultural desert land with saline groundwater irrigation and soil amendment for food security in Egypt. The following sections provide the summary literature review organized by system components, followed by a review of systems-level considerations and modeling recommendations. The conclusion provides a summary of the synthesized critical challenges and ideas for solutions.

2. Effects of Irrigation with Saline Groundwater

2.1. Impacts of Salinity on Crop Growth

The rise in food demand, coupled with the increase in water requirements to boost global crop production, amplifies stress on the limited available freshwater resources [34]. In arid and semi-arid regions, where the surface water is usually insufficient to meet the irrigation water demand, groundwater is used to make up for such deficits [35]. In Egypt, which is located in an arid and semi-arid region, the use of saline water for irrigation with limited fresh water is common and is expected to increase in the future. Egypt has the following major aquifer systems: the Nile Valley and Delta aquifer, Nubian Sandstone aquifer, Moghra aquifer, Coastal aquifers, Fissured Carbonate aquifer, Pre-Cambrian Fissured and weathered hard rock aquifers, groundwater in Sinai, and groundwater in the Western Nile Delta aquifers [36]. The groundwater in all aquifer systems contains substantial salinity with a wide range from about 200 ppm to 12,000 ppm, and the aquifer systems have hydraulic conductivity ranging from 1 m/day to 100 m/day—the Nile Valley and Delta aquifer has the highest hydraulic conductivity among the eight aquifers [37]. Thus, excessive pumping of groundwater to irrigate the crops at a rate higher than the rate of recharge could cause intrusion of saline water from either the fossil groundwater or seawater [38].

Salinity causes negative effects on both the soil and plant health. However, the extent of the effects on different plants can vary in degree. Also, there can be different levels of effects depending on the developmental stages of plant growth. During the early vegetative stages, crops are more sensitive to salinity and pronounced symptoms such as leaf stunting and tip leaf discoloration [39,40]. One of the major effects of salinity on the normal growth of plants comes from cellular shrinkage due to dehydration or physiological drought generated from osmotic stress caused by excessive salt ions [39]. Grains such as wheat and rice are especially susceptible to salinity in soil and water stress during the maturing stage—salinity could induce early flowering and deformed reproductive organs in wheat [41]. Both sodium and chloride ions adversely affect plant growth in the long term by limiting photosynthesis that results in inhibition of the growth and development of agricultural crops [39].

Plants' roots are the main organ responsible for water and nutrient uptake, and the first inter-face to sense and respond to salinity stress. Therefore, investigating the root response of crops under salinity stress is important for developing climate-resilient crops [42]. Compared with shoot traits such as flowering time and yield, root traits are not a common plant breeding objective due to the inaccessibility of the root system and the lack of the requisite genetic data associating root phenology and molecular biology with adaptive responses to salinity [43]. However, the development of high throughput phenotyping platforms has recently permitted the association of root phenes with water acquisition from drying soil in cereals including rice [44,45] and maize [46].

Salt stress under osmotic or ion toxicity results in stunted root growth [47]; the degree of deterioration is associated with several factors—most importantly, species, salinity level, and soil type [48]. At the seedling stage, the inhibition of cotton root growth could be related to the elevated concentration of Na^+ at the expense of K^+—an effect that could be partially mitigated by the addition of Ca^{++} [49]. Salinity, in most cases, damages the root system much less than the shoot, which results in a higher root/shoot ratio compared to control conditions [50]. Nevertheless, this phenomenon might not be a universal response within plants due to the variation in the range of salinity stress tolerance as seen in *Capsicum annuum* and *Chloris gayana*, where roots were damaged by salinity more than shoots [51]. Generally, it is thought that roots, unlike shoots, could be more sensitive to sodium ion toxicity rather than osmotic factors, particularly in the seedling stage of cereals such as maize and rice [52,53].

Root system architecture (RSA) is an important determining factor in a plant's capacity to access water and nutrients and, therefore, in crop productivity. Structural traits of the roots (e.g., total root depth, root angle, or lateral roots' number/branching density) showed a high degree of plasticity in saline soil from the early vegetative stage up to maturity and crop harvest. The shape of the RSA of mature plants is eventually determined by early root responses to gravity in saline soil [54]. Halo tropism or the disturbance of root gravitropism under salinity has been reported in many plants, such as *Arabidopsis*, sorghum, and tomato [55]. Interestingly, the primary roots of plant seedlings could escape or circumvent saline-affected soil by redirecting roots to access and extend into less salt-content soil located in a direction away from the main root vector angle [56]. Over the early stages of a crop plant's life cycle, high salinity inhibits primary root growth together with a number of lateral roots due to the reduction in the formation of meristematic tissue, called the lateral root primordium (LRP) [57]. On the other hand, Ref. [58] reported that lateral root growth increased as a result of increasing the salt concentration of irrigation water to 100 mM NaCl. Interestingly, the elevated increase in Na^+ uptake by the increased surface area of the emerged lateral roots showed no negative effects. The potential negative effects were apparently mitigated by a significant reduction in hydraulic water conductivity.

2.2. Impacts of Salinity on Soil Health

Physical, biological, and chemical characteristics of soil are all included in soil health. As a result, any impact on any or all of the soil properties will seriously harm the health of the soil. Furthermore, water shortage is highly pronounced in arid and semi-arid countries and has become a worldwide problem of increasing seriousness. Thus, low-quality water such as saline groundwater is commonly used to dominate water shortage [59]. Therewith, saline groundwater naturally has solutes of variable concentrations, and its application can be noticeably affected by soil and plant properties. Due to salt accumulation in the root area, irrigation with saline water generally causes increasing soil salinity and greater salinity threats to plant growth [60].

Furthermore, climate changes increase the intensity of the salinity problem. In reality, global warming leads to increased temperature and precipitation fluctuations, with consequent increases in evapotranspiration and the reduction of salt leaching [61]. Consequently, the presence of salt in the soil area increases. The groundwater salinization causes problems such as soil compaction [62], a reduction in the fertility of the soil [63], and, ultimately, a reduction in crop yield [64]. For example, the compaction of clay soil particles is affected by the valence of the adsorbed cation and the salt concentration. In general, the larger the valence of the adsorbed cation, the closer the cation is held to the clay particle [65]. For example, calcium (with a valence of two) is held more closely to clay particles than sodium (with a valence of one). Thus, the soils that have a relative predominance of calcium adsorbed to the clay particles will have a high water transmission potential (i.e., permeability) compared to those clay soils that are predominated by sodium adsorption (i.e., sodic soils). Soil's structure and water transmission potential are negatively affected by increasing amounts of sodium that comprise a clay soil's cation exchange capacity (CEC) [65]. The swelling and dispersion of clay particles due to the soil salinity can cause clogging of micropores (the spaces between clay particles), which, in turn, reduces the soil's hydraulic conductivity [66]. Thus, soil salt accumulation is a major soil degradation process that threatens ecosystems and is a critical global problem for agricultural production. The direct effects of soil salinization include a reduction in agricultural productivity [64] and increased environmental concerns [67], while the indirect and ultimate effect results in economic losses [68].

The extent of soils affected by salt accumulation has increased globally [69]. Salinization can happen either naturally or as a result of environmental factors brought on by management decisions. Numerous factors contribute to soil salinization, including the presence of soluble salts such as sodium, calcium, and magnesium sulphates in the soil, a high water table, a fast rate of evaporation, low annual rainfall, and the use of water that is of poor quality [60].

For irrigation, water quality suitability needs to be determined. As pointed out earlier, freshwater—especially fresh groundwater—is rapidly diminishing [70], and the remaining water is becoming saline [71]. Therefore, it is necessary to consider the use of saline water for irrigation in the face of diminishing freshwater resources. Consequently, opportunities and challenges should be highlighted and should be focused on addressing soil salinity. Opportunities to alleviate salinity problems include adding improvements, cultivating salinity-tolerant varieties, irrigating in a timely manner, mixing fresh and saline water, and improving drainage and soil maintenance.

3. Soil Amendment to Increase Crop Production in Salt-Affected Soils

In arid and semi-arid regions, such as Egypt, groundwater irrigation is a common alternative for desert agriculture, especially when surface water availability is limited [72]. However, the presence of excessive salinity in groundwater and soils can significantly reduce agricultural crop yields by triggering serious negative effects on soil properties and plant traits. This is a critical challenge to agricultural producers and policy-makers for achieving sustainable desert/biosaline agriculture and food security [73]. The effectiveness of the technical options available to minimize the salinity effects is unclear, however their implementation is necessary for the planning of desert agricultural systems using saline groundwater.

With the use of saline irrigation water, various approaches to improve crop production against salinity stress have been implemented. These include (1) the planting of salt-tolerant crops, (2) the use of more efficient irrigation methods (e.g., drip irrigation system), (3) salinity leaching, and (4) treatment and amendment of saline soil [74,75]. In arid and semi-arid regions, the salinity leaching method with (artificial) drainage is typically used to manage soil salinity [75]. By ensuring an effective salt "balance" between soil drainage water and the plant root zone, agricultural crop yields can be maintained at adequate production levels. In this approach, the irrigation and/or drainage specialist determines an appropriate moisture leaching fraction that results in an acceptable crop yield at a reasonable cost [76,77]. Thus, this option produces the effects of not only removing the salinity from the root zone physically, but also recharging the groundwater and managing the water table level [75]. However, in locations where only saline irrigation water is available and freshwater availability is limited, the addition of specific soil amendments may be the only cost-effective alternative for sustaining agricultural crop production levels [78].

Soil amendments have been widely employed to improve poor soil quality—including the negative effects of soil salinity—for various crop types [79]. Soil amendments can be classified into two types: (1) organic amendments, including solid waste compost, fly ash, and biochar; and (2) inorganic amendments, such as gypsum, langbeinite, and zeolite [79–82]. One of the common soil amendments is the application of biosolids, i.e., the residual organic solids generated from the physical and biological treatment of municipal wastewater [83]. Land-applied biosolids improve both the aeration and drainage capacities of saline soils through porosity enhancement [84]. Moreover, the organic fraction of biosolids increases the saline soil's available water holding and cation exchange capacities [85]. However, biosolids land application for agricultural production is not legal in Egypt, because the biosolids contain organic pollutants that pose significant risks to public and environmental health [86]. In other countries, this practice has strict regulatory limits on human pathogens, heavy metals, and emerging contaminants such as microplastics [87–90]. For example, the United States (U.S.) and Europe strictly manage the quality criteria in terms of regulated pollutants and pathogens in biosolids and limit the sites and land application rates of the biosolids [91,92]. The U.S. legally stipulates biosolids land application at rates that are equal to or less than the crop-specific agronomic rate, i.e., the rate of amendment application that provides nutrients (e.g., nitrogen or phosphorus) at a level that meets the crop-specific needs [92]. Limiting the amendment application rate to the agronomic rate protects public health and the environment by minimizing the amounts of excess nutrients that could potentially impact surface and/or groundwater resources.

Recently, the application of biochar (or its mixture with other organic matters such as vermicompost) has been receiving increased attention from agricultural producers as a potential option to improve crop yields in salt-affected soils [93–95]. Biochar, which is generated through the pyrolytic treatment of various types of organic residuals, differs from charcoal only in that it is produced specifically with the intention of soil application [96]. Beyond sustaining agricultural productivity, additional benefits ascribed to biochar soil application include the neutralization of acidic soils, increased retention of soil moisture (water holding capacity), improved soil aeration, enhanced retention of fertilizer and nutrients, reductions in soil-based greenhouse gas emissions (primarily N_2O and CH_4) and increased carbon sequestration [97–100].

Numerous studies have reported enhanced soil quality and crop productivity following biochar land application through quantitative investigations for different types of soils [101,102], feedstocks [103–105], and crops [101,106–108]. Previous studies, including [108–110], have also investigated the agricultural effects of biochar on the soils in Egypt. For example, Ref. [111] investigated the crop productivity effects of biochar application to sandy soils in Egypt under deficit irrigation water conditions. They suggested an optimal biochar rate that produced about 25% reduction in the irrigation requirement. Ref. [112] examined the effects of biochar—derived from different feedstocks (rice straw and soybean)—on the fertility of reclaimed sandy soil in Egypt and suggested a biochar rate that yielded the largest growth and productivity of wheat in the sandy soil. Ref. [113] offered the application of organic-waste-derived biochar (e.g., poultry manure) coupled with a nitrogen fertilizer to improve wheat productivity and soil organic matter content in sandy soil in Egypt. Ref. [114] tested the effects of adding biochar with phosphate fertilizer on soil fertility and wheat yield in clay-textured soil in Egypt; the authors observed the promising contributions of the co-application of biochar and fertilizer to reducing the bulk density of clay soils and improving the soil quality (e.g., aggregate stability, saturated hydraulic conductivity) and wheat productivity (e.g., grains per spike).

Over the past decade, with increasing attention on the land application of biochar as a soil amendment, the biochar effects on salt-affected soils (saline soils or saline water irrigation) have also been investigated. Ref. [115] found that the biochar application improved the soil quality (e.g., soil pH, soil organic carbon content, cation exchange capacity, phosphorus availability) of saline-sodic soils in a 56-day incubation experiment. Ref. [116] quantified the effectiveness of biochar—which was produced from wood chips of golden wattle—on plant growth and nutrition in saline-sodic soils in a 180-day biochar application. For the biochar application with saline irrigation water, Refs. [117,118] identified that biochar application at a specific mass ratio had the clear effect of reducing the salt stress of sandy soil and plants under saline water irrigation and, in turn, improving the vegetative growth (i.e., tomato and wheat yields). Refs. [119,120] evaluated the effects of biochar application with freshwater and saline water irrigation; their two-year experiments quantitatively demonstrated the improvement of soil quality and wheat productivity, which had been significantly reduced due to saline water irrigation. From these studies, it is noted that the biochar land application can substantially contribute to achieving the target levels of crop production in arid areas, using saline groundwater for irrigation.

However, a few studies have also noted concerns over the potential negative side effects of biochar land application [121]. For example, Refs. [119,122] quantitatively demonstrated that excessive application of biochar could potentially increase soil salinity and degrade the soil's hydraulic properties (e.g., saturated water content, field capacity, permanent wilting point, and plant-available water). In addition, previous studies identified the effectiveness of biochar land application on soil amendment and plant growth; however, they found inconsistent results on the positive and negative effects of the biochar application [122]. The underlying scientific mechanisms behind these observed effects and the quantification of their longevity remain unknown. Thus, further efforts to evaluate the short- and long-term effects of biochar land application under various conditions (e.g., soil texture, plant types, temperature, soil and irrigation salinity, biochar properties and feedstocks, biochar application amounts) are required to guide the proper use of biochar with saline irrigation water.

Unlike biosolids, the acute and long-term effects of biochar land application on public health, economics, and the environment have not been extensively studied. A few studies have provided insight into some of the apparent tradeoffs that exist between biochar's beneficial use and public health. For example, while biochar produced from maize cobs has been found to be effective in improving soil fertility in developing countries, the air pollutants associated with pyrolytic emissions—namely, PM_{10} (particulate matter of less than 10 microns) and carbon monoxide (CO) —have had serious deleterious effects on human health in those communities [123]. Unfortunately, technologically advanced pyrolytic kilns with air emission controls are financially unavailable for many of these agricultural producers [123]. A full understanding of the tradeoffs between social, economic, and environmental impacts and the agricultural benefits associated with land application of biochar is required if this approach to mitigating soil salinity is to become standard agricultural practice. To quantify and predict such tradeoffs, it is necessary to establish a science-based mechanistic and systemic understanding of how biochar processing (raw materials and pyrolytic conditions) affects the final biochar characteristics, and of how those characteristics, in turn, impact soil properties and crop yields.

4. Challenges and Ways Forward

Based on the review of the effects of saline groundwater irrigation on soil health and crop growth, this section discusses the challenges and opportunities associated with the use of systems thinking to achieve a sustainable desert agricultural system with saline groundwater irrigation. Figure 1 summarizes a conceptual scheme for a systems thinking approach with dynamic drivers, feedback interactions, and system strategies.

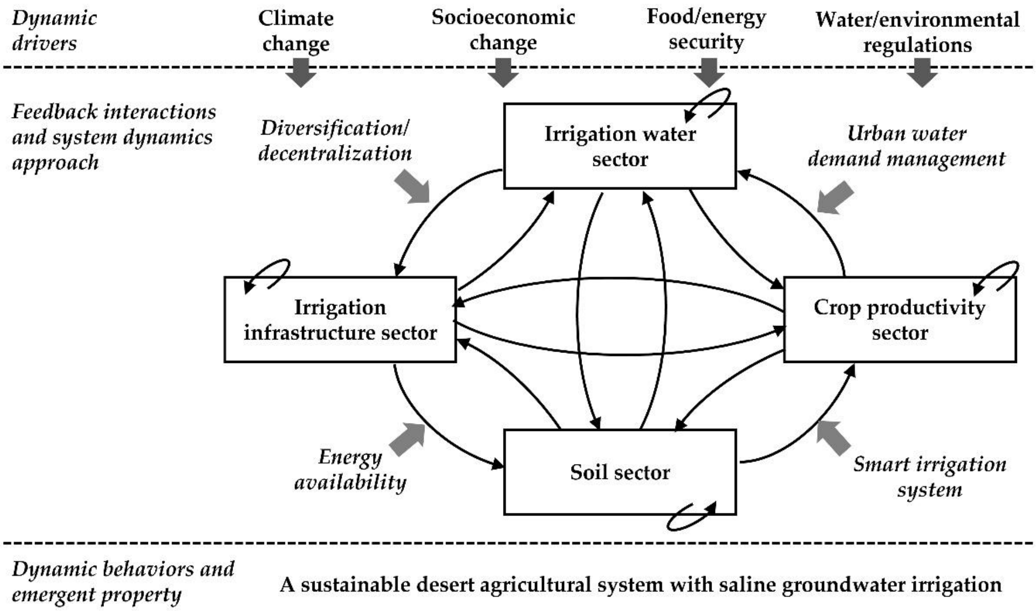

Figure 1. A systems thinking approach for a sustainable desert agriculture system.

4.1. Systems Thinking to Understand Feedback Processes in Desert Agricultural Systems

A reclaimed desert agricultural system is considered in Egypt as a solution to improve food security under climate and socioeconomic changes. However, a critical concern is the availability of suitable irrigation water [124]. Egypt has a large water resource—i.e., the Nile River—for irrigation, yet considers the use of local groundwater sources because of the need for greater amounts of water than what the Nile River may provide in order to establish a more reliable and robust system. However, the use of local saline groundwater in Egypt poses challenges in mitigating the effects of salinity on soils and crop production [125,126]. As described in the previous section, soil amendments can be applied to enhance salt-affected soils and mitigate the effects of saline groundwater irrigation. However, decisions regarding the use of saline groundwater with soil amendments will have sustainability challenges including potential public health ramifications (e.g., emerging contaminants contained in soil amendments), economic implications (e.g., farming production costs versus sales profits), and environmental quality considerations (e.g., salinity in soil and other water resources) [79,127–129]. Thus, establishing a desert agricultural system satisfying the crop productivity demand requires consideration of how to maximize socioeconomic benefits while minimizing the long-term environmental impacts [130].

In general, understanding the long-term impacts and implementing practical solutions for the challenges is not straightforward [131]. This is because agricultural systems have a complex structure with dynamic feedback interactions in their subsystems, including the irrigation water sector (e.g., irrigation water resources), infrastructure sector (e.g., irrigation channels and power supply from existing power grids or renewable energy sources), soil sector (e.g., soil salinity and fertility), and crop productivity sector (e.g., plant growth and crop yield) [132–140]. A change in a component (e.g., soil salinity) in a subsector can generate changes in other connected sectors' components (e.g., crop productivity, soil amendment, and freshwater irrigation) and, in turn, affect back to the original one in a holistic viewpoint—i.e., feedback process [141].

Figure 2 shows a Causal Loop Diagram (CLD) showing an example of the feedback processes that can be considered for desert agricultural systems in Egypt. The CLD is commonly used to qualitatively understand the dynamic feedback interactions that are produced by critical system components and their causal relationships [131,141]. In the

CLD, the positive label on a causal link implies that an increase/decrease in the state of a component causes an increase/decrease in the state of a connected component. The negative label indicates that an increase/decrease in a component causes a decrease/increase in a connected component. Thus, these positive and negative causal links create feedback loops, which determine the system behaviors such as reinforcing ('+') or balancing ('−'). Further details of the CLD can be found in [141]. The specific description for the feedback interactions in Figure 2 is as follows:

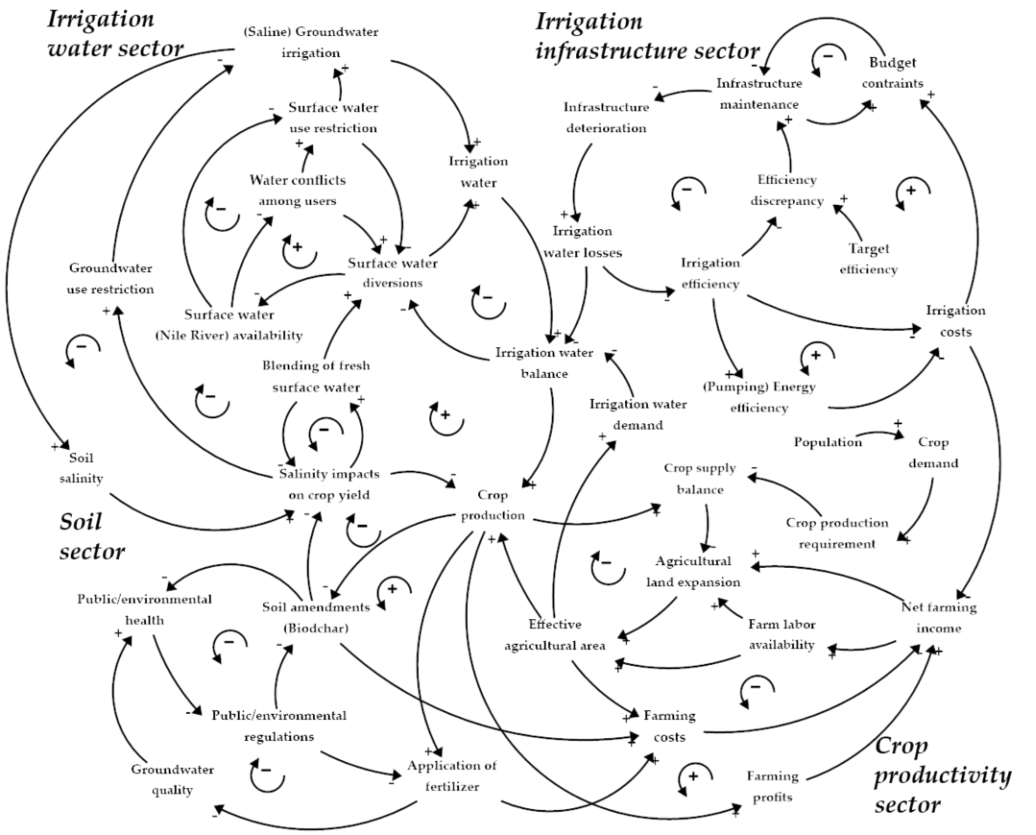

Figure 2. An example of a CLD for feedback interactions between the irrigation water, irrigation infrastructure, soil, and crop productivity sectors.

(1) ***Irrigation water sector***: Egypt has an enormous reliance on the Nile River for water resources, which makes up more than 95% of total water demands in a given year [130]. The agriculture sector consumes the largest portion of the water resources (accounting for about 85% on average) [137]. An increase in Nile River diversions for agricultural irrigation of desert land will consume more river water, which leads to increased competition among the water users. This can result in more exploitation of the Nile River, with growing water conflicts among the users, which can consequently limit the water diversions and reduce the use of irrigation water from the Nile River [142–144]. In addressing this feedback process, the use of groundwater will reduce the Nile River diversions, improve irrigation water availability, and, in turn, mitigate the water conflicts among users [130]. However, the increased use of the saline groundwater requires more blending of fresh water from the Nile River to mitigate the negative effects of salinity (e.g., decreases in crop productivity). These results lead to a feedback process in which more water from the Nile River is diverted, which yields even greater conflict among water users. With growing water competition and conflict, the use of saline groundwater will be subject to greater restrictions, which, in turn, will bring about additional irrigation problems. Thus, a lack of consideration of these feedback processes and their interactions will lead to underestimating the requirement of total irrigation water availability—including the contribution of saline groundwater irrigation—for expanding desert agriculture.

(2) ***Irrigation infrastructure sector*:** Irrigation infrastructure such as irrigation canals, groundwater pumps, and drip systems deteriorates with age and, if not replaced and upgraded, will have low irrigation efficiency. One of the goals for irrigation infrastructure management would be to improve irrigation efficiency by maximizing the consumptive portion of supplied water for agricultural productivity [145]. The deterioration of irrigation infrastructure can produce low irrigation efficiency, leading to low water availability due to increases in pumping costs and water losses. Meanwhile, regular maintenance activities such as the replacement of pumps and irrigation drip lines or canal lining can be implemented to achieve the management goals, which reduces the deviation of the irrigation efficiency from a set threshold [145]. However, the proper maintenance activities incur high but required financial costs, which will cause pressure in terms of the funding needed for their implementation. A limited or insufficient financial allocation to cover these costs can constrain maintenance activities and, in turn, result in rapidly deteriorating infrastructure. Thus, there is a need for cost-effective management options with sufficient affordability to plan desert agricultural systems that depend on groundwater use.

(3) ***Soil sector:*** The use of saline groundwater for irrigation increases the soil salinity, which lowers a soil's hydraulic conductivity and reduces crop yields [146]. Thus, desert agricultural systems require the use of innovative options including the use of soil amendments (e.g., biochar) or blending of freshwater with saline groundwater to mitigate the adverse effects of high salinity on crop yields [146–149]. In this context, irrigation with saline groundwater increases the soil salinity, which leads to an increase in the diversion of freshwater supplies from the Nile River to leach out the accumulated salt from the soil and root zone [79,150]. This increase in the demand on diversions from the Nile River will increase local water conflicts, which will limit the opportunities to blend the Nile River with saline groundwater, and, in turn, amelioration of the soil conditions [151]. Furthermore, an increase in the use of soil amendments (e.g., biochar), which can reduce the amount of freshwater supplies and salinity stress on plants, can have adverse effects on public and environmental health, e.g., biochar can contain emerging pollutants such as carcinogenic polyaromatic hydrocarbons (PAHs) [152]. The presence of emerging contaminants can limit the use of soil amendments due to existing public health and environmental regulations [129]. Thus, improving soil conditions through the mitigation of salinity effects requires a comprehensive understanding of the interactive feedback processes related to water resources availability, public safety, and environmental protection.

(4) ***Crop productivity sector:*** Egypt faces food security challenges to keep pace with its rapid population growth, which experts estimate will require a 70% increase in agricultural crop production by 2050 [130]. However, the agricultural production from reclaimed desert lands, which accounts for about 25% of the total fertile agricultural area, only contributes to 7% of total agricultural production in Egypt [130]. The limited availability of irrigation water or increased soil salinity can reduce crop yields, which leads to decreased agricultural production and farming income. The reduced farming income can increase the movement of populations away from the farming areas, which reduces the level of available farm labor [137]. Insufficient availability of labor can limit farming activities and further reduce crop yields and farm income [137,153]. Furthermore, the growing use of the Nile River for crop irrigation and the enhanced application of soil amendments (e.g., biochar and fertilizers) to increase crop productivity will increase the financial investment in irrigation infrastructure and soil management programs. These required investments will result in increasing agricultural costs, which, in turn, will reduce net farming income. In addition, the application of fertilizers and pesticides to improve crop yields can deteriorate soil quality in the long term and increase groundwater contamination [154,155].

Chemical contamination of groundwater may result in negative impacts on human health and the environment (e.g., Nile River water quality and ecosystem, greenhouse gas emissions) [156–160]. From a holistic feedback perspective, the legal regulations or policies aimed at protecting human health and the environment will limit the soil amendment activities, which, in turn, will limit the improvement of agricultural crop yields [161,162].

The interactive feedback processes in desert agricultural systems can act as resources reinforcing or constraints balancing the systems' behaviors (e.g., irrigation water availability and crop productivity). The dynamics and complex interactions of the feedback processes can create the unexpected, uncertain performance of the agricultural systems—which is called the "emergent property (phenomenon)" in complex systems [131,163]. An example of the emergent property would be the level of soil fertility for plant growth and productivity, which is determined by the physical, chemical, and biological interactions between the plant (e.g., crop types and nutrients), animal (e.g., soil organisms and animal health), human (e.g., cultivating intensity and food production), and climate dimensions [164]. Failure to consider the structural and feedback interactions can bring misunderstanding of the counterintuitive consequences (emergent property) from the implementation of a desert agricultural system with blending diversions of the Nile River with saline groundwater and/or the application of soil amendments for improving agricultural crop production. Thus, the decision-making process on a sustainable desert agricultural system needs to follow an integrated and holistic view, considering the nonlinear and dynamic feedback interactions across its subsystems and associated factors [137,141,165–167].

4.2. Need to Address Dynamics in Drivers

Feedback processes and their interactions are directly affected by dynamic external drivers such as climate and socioeconomic changes (e.g., market prices, population growth, and domestic water demand), energy availability (e.g., energy crisis), and policies (e.g., environmental regulations and subsidies), which can induce system behaviors that are unexpected in the decision-making process [168–171]. Previous researchers, e.g., [171], predicted that the changing climate with increasing temperatures and precipitation variations could reduce the flow of the Nile River by 12%. Thus, the reduced water availability from the Nile River can lead to more competition and conflicts among the end-users of the Nile River and, in turn, increase the constraints on the use of irrigation water from the Nile River. In addition, the reduced discharge of the Nile River can increase soil salinity in the Nile Delta region, which leads to more requirements of freshwater in saline groundwater irrigation and soil amendment to mitigate the salinity effects [150,171].

Rising sea level due to climate change can also increase the intrusion of salt water into the shallow aquifer and, in turn, lead to an increase in groundwater salinity—e.g., the increase in salinity in the Nile Delta region due to climate change is anticipated to be about 27% [130]. Thus, with the increased use of groundwater irrigation, salt water intrusion exacerbates soil salinity and eventually, will limits the use of saline groundwater, which affects the feedback process related to irrigation water availability and crop productivity.

The projections of climate change in Egypt indicates an increase in temperature of 3.1 °C to 4.7 °C [24,172]. This temperature rise can produce a significant increase in evapotranspiration, which can increase by 4% as a result of a 1 °C temperature rise in Egypt [130]. The increased evapotranspiration increases irrigation demands and elevates the salinity of the soil and groundwater, which will limit the use of groundwater for irrigation [150]. In addition, climate change has direct impacts on the growth, productivity, and quality of most crops [130,171]. In Egypt, wheat yields are expected to decrease by about 20% in 2060 due to changes in temperature and water regime [130,171]. Furthermore, the reduced discharge of the Nile River due to climate change—which is expected up to 25% of current discharge based on GCMs [171,173]—can change the irrigation patterns and, in turn, have significant impacts on soil salinity and crop yields [171].

Egypt is experiencing a rapid increase in population growth. The population has doubled since the mid-1980s and the urbanized areas have increased substantially. The increasing food demand as a result of the population growth, urbanization, and increase in living standards has highlighted the need to expand agricultural production. This expansion requires more irrigation water, which will exacerbate the competition among the end-users of the Nile River. Furthermore, the growth in food demand leads to a need to increase crop yields and agricultural productivity—a need for an increase in agricultural production of about 70% by 2050 [130]. This increase in agricultural productivity will require the increased application of soil amendments and methods to ameliorate the effects of soil salinity, which can influence the various feedback processes related to irrigation water availability, soil amendment application, and crop productivity.

The recent and rapid growth of the population and economy of Egypt has increased the demand for energy security and availability because of the increased need for more energy production [130]. The deteriorating efficiency of groundwater pumps (or drip irrigation systems) can increase energy consumption (and pumping costs) for groundwater withdrawal [174]. However, the energy and financial constraints caused by increasing energy demands in the agriculture and non-agriculture sectors can limit the energy consumption to pump groundwater, which eventually affects the feedback processes related to the irrigation water availability and infrastructure. In addition, the increase in energy consumption—especially by fossil-fuel generating units, may lead to more emissions of greenhouse gases—which have adverse impacts on climate change and the environment [130,175]. Thus, the policies addressing energy conservation and environmental restrictions can also affect the feedback processes related to irrigation water availability and infrastructure.

From the understanding of the external drivers' impacts on feedback processes in agricultural systems, it should be noted that the drivers can limit the sustainability of using saline groundwater with or without soil amendments to support desert agricultural systems. The drivers are changing, dynamic, and uncertain. Thus, there is a need to evaluate how the drivers and their combinations affect the feedback processes and to determine what consequences and adaptive strategies can be produced in a holistic viewpoint in short- and long-term periods for sustainable desert agricultural systems.

4.3. The Need for a System Dynamics Approach in Decision-Making

The agricultural systems built on reclaimed desert lands, as water-agriculture-socioeconomic systems under dynamic and various drivers, are inherently complex. As described earlier, these systems can have delayed, unintended, and unexpected consequences in system behaviors arising from feedback processes with management interventions [176]. Thus, the planning of saline groundwater use for desert agricultural systems needs to be addressed with systems thinking and long-term strategies to identify the emergent properties among the water, agriculture (e.g., soil, biophysics, and infrastructure), environment (e.g., climate), and socioeconomic sectors and to minimize the unintended system behaviors [176–178].

Systems thinking considers multifaceted and interacting components in a holistic view for planning a system [177]. In this regard, the system dynamics (SD) approach is uniquely suited to understanding and analyzing the complex, nonlinear, and dynamic behaviors of agricultural systems governed by complicated interacting feedback processes with a time delay [137,176]. The SD approach emphasizes the relationships and interactions among the system's components rather than considering the individual components in isolation [137,141]. The integrative characteristics of the SD approach allow for the coupling of the physical, socioeconomic, and environmental components that comprise agricultural systems. Thus, the SD approach underlines the engagement of multifaceted stakeholders—who are involved in the planning of agricultural systems impacted by saline groundwater irrigation and the addition of soil amendments to support agricultural production in desert lands—and their inclusive decision-making with transparency and multiple criteria [142].

In this context, several studies [137,176,179–183] have employed the SD approach to evaluate the feedback interactions between the water irrigation, socioeconomic, crop productivity, and environmental sectors and the impacts of external drivers such as population growth, land-use changes, and climate change. These studies have addressed irrigation water management (e.g., groundwater protection and wastewater reuse), agricultural production (e.g., crop yields), conservation of natural resources, and water and environmental policies. However, few efforts have been made to investigate the feedback interactions in sustainable agricultural systems in newly reclaimed desert lands—especially those using saline groundwater and soil amendments. Reclaimed desert agricultural systems with saline groundwater irrigation need to produce more food from limited land, water, and financial resources. The challenge is to increase agricultural production to meet growing food demands with more socioeconomic benefits and minimal environmental impacts [184]. Thus, decision-making based on the SD approach needs to consider the tradeoffs between water availability, agricultural productivity, soil, infrastructure, socioeconomics, and environment sectors within the constraints of limited financial resources to achieve sustainable desert agriculture.

4.4. Sustainable Desert Agricultural Systems with Saline Groundwater Irrigation

4.4.1. Diversification and Decentralization in Irrigation Systems

Reclaiming desert land for agriculture with saline groundwater irrigation will pose sustainability challenges for maintaining the required agricultural productivity given limited water and financial resources and uncertain, dynamic drivers, as described above. A simple measure for sustainable irrigation and agriculture is the modification of cropping patterns, as a demand-side adaptation option, that can result in reduced irrigation water demand [171,185]. However, modification of cropping patterns can be misinterpreted due to the need to increase the security of the targeted agricultural crops [171]. In this context, an increase in water resources and system efficiency is a more effective measure for sustainable agricultural production than tracking the level of cropping pattern modification [171].

However, the drivers that affect irrigation have high statistical uncertainty [186]. The uncertainty in climate change further exacerbates the complexity of predicting the climate impacts combined with socioeconomic changes—e.g., the variation in the flow of the Nile River from −60% to 45% for multiple general circulation models (GCMs) [187], or in the range from a 30% increase to a 77% decrease [188]. The uncertainty in local drivers can lead to debates and conflicts among stakeholders over their impacts and importance during the decision-making processes [189]. Thus, addressing the uncertainties of the various drivers and their impacts is the primary challenge in decision-making for sustainable irrigation systems in reclaimed desert agriculture.

In this context, various fields have employed diversification and decentralization strategies to address uncertainties in their systems and environments. For example, military forces have considered more diversity in weapons and soldiers' roles to handle various missions [190,191]. Financial managers have stressed diverse and decentralized assets in a financial portfolio for higher returns and lower risks in unpredictable market environments [192,193]. It is well known that the diversity and decentralization of ecosystem species and their functions are critical attributes for the ecosystems' survival in uncertain environments [194–196]. Moreover, the "Law of Requisite Variety: only variety can destroy variety", introduced and verified quantitatively in the field of Cybernetics using the concept of entropy, describes how variety (i.e., decentralization and diversification) in systems can enable active and adaptive responses to uncertain disturbances [197,198]. Thus, incorporating diversified and decentralized options in designing, operating, and managing irrigation systems in desert agriculture will contribute to the systems' flexible and resilient responses against the complicated impacts of uncertain and dynamic drivers.

An example could be an irrigation system that is supported by diversified and decentralized water sources including harvested rainwater, agricultural return flow, and treated wastewater, in addition to the Nile River and groundwater [199,200]. Such an irrigation system, in turn, can reduce the dependencies on the Nile River and saline groundwater for irrigation. Thus, the irrigation system can increase irrigation water availability from multiple sources that can partially or completely replace a water resource under unexpected disruptions—e.g., significant water shortages in the Nile River due to unexpected drought. By means of water supply from diversified and decentralized water sources, the irrigation system can minimize irrigation losses and quickly recover the irrigation performance in the face of unexpected disruptions [201–204]. The effects of such an irrigation system with multiple water sources can enhance the feedback loops toward an increase in water availability.

This option is also well aligned with a sustainability strategy entailing the use efficiency, conservation, and recycling of water to maximize socioeconomic benefits and minimize environmental impacts [205–207]. For example, in Egypt, more than 80% of supplied freshwater is used for agriculture, with 25% of the irrigated water becoming return flow [208]. The return water from agriculture is water drainage into the Nile River. The return water generally includes contaminants that degrade the environment, e.g., the water quality of the Nile River and adjacent canals [209,210]. Thus, the reuse of return flow is an option that reduces water resource demand while mitigating the release of potential water pollutants.

4.4.2. Urban Water Demand Management

Another strategy for sustainable irrigation systems in desert agriculture is urban water demand management with optimal allocation of water resources [151,211]. This option can mitigate the diversion demands on the Nile River and the competition among the end-users by reducing urban water consumption [212]. However, the water requirements of various sectors are different and are changing over time. The current water allocations of the Nile River and groundwater may be inadequate for future water demands. In this regard, diversification and decentralization options (e.g., distributed alternative water sources) in urban water systems, along with the stepwise tradeoffs between urban and agricultural water resources, will also help improve the availability of irrigation water resources in the long term, considering the dynamics and uncertainties of climate and socioeconomic changes.

4.4.3. Sufficient Energy Availability

An increase in energy consumption in Egypt due to rapid population and economic growth can limit the operation and efficiency of the irrigation infrastructure (e.g., pumping energy for groundwater extraction) under limited energy availability. In addition, the use of diversified water resources for sustainable irrigation water or desalination technologies (e.g., reverse osmosis, electrodialysis, nanofiltration, distillation, capacitive deionization, or solar humidification and dehumidification) to dilute the salinity in groundwater may also lead to an increase in the energy consumption (requirements) of the desert agricultural systems [213–217]. In this regard, renewable energy systems such as wind turbines, solar photovoltaic cells, and hydropower—which can be configured as the components of a microgrid—would contribute to addressing the energy constraints for irrigation infrastructure systems and mitigating energy supply disruptions resiliently in the case of emergencies [130,218–221]. Renewable energy sources are mostly regarded as eco-friendly systems with minimal environmental impacts compared to conventional fossil-fuel-based systems [222]. However, incorporating renewable energy sources into the energy supply (or existing grid) for desert agriculture systems has a number of challenges due to the intermittent nature and fluctuation in their energy generation and the storage of generated renewable energy [223–225]. Thus, to improve energy availability from renewable energy sources, a well-designed portfolio of multiple renewable energy sources depending on local conditions (e.g., climate and energy demand) and the planning of operational tradeoffs between the renewable energy sources and existing energy grid depending on energy availability and emergencies (e.g., peak irrigation load time) are suggested.

4.4.4. Smart Irrigation System

Improving irrigation systems' efficiency will also contribute to sustainable water irrigation and desert land agriculture. In this regard, a smart irrigation system with sensors and controllers can be considered [226]. Many agriculture systems irrigate water at a specific or regular time and duration via timers of manual controllers. This type of irrigation system has contributed to the waste or over-irrigation of water without considering the irrigation requirements based on climate and soil conditions—e.g., about 30% of irrigated water is wasted [227]. Smart irrigation systems with sensors (e.g., soil moisture sensors), communication, analytics, and controllers (e.g., remote timers) can collect data on soil conditions and irrigation facilities in real time and predict real-time irrigation requirements along with climate conditions such as temperature, humidity, antecedent rainfall, and winds [228–230]. Thus, smart irrigation systems facilitate the application of more accurate irrigation amounts and optimal timing for effective plant growth without excessive waste and, in turn, contribute to improving irrigation efficiency and water savings for sustainability [227].

4.4.5. Active Participation of Stakeholders

Many agricultural stakeholders, including farmers and system managers, have learned how to decide and adjust their plans and adaptation activities based on their practical experience. In this context, sharing their experiences and portfolios of adaptation strategies among the multiple stakeholders can substantially and effectively improve the stakeholders' knowledge and adaptation capacities [231]. Thus, there is a need to incorporate strategies for learning, including the creation of educational environments that meet the needs of multiple stakeholders faced with desert land agricultural system planning under uncertainty.

The success of irrigation infrastructure management requires the active engagement of various internal and external stakeholders in the institutional, technical, financial, and farming business sectors [232–234]. The conflicts and tradeoffs among the stakeholders can act as constraints or synergies for the irrigation infrastructure management activities. Thus, the systematic, comprehensive understanding of the conflicts and tradeoffs among the stakeholders will help in the practical implementation of the required infrastructure management activities.

5. Conclusions

Expanding agricultural systems in arid and semi-arid regions is an immediate solution to address food security issues arising from population growth and global climate changes. However, a major challenge is the use of scarce water resources in an equitable and sustainable way. In Egypt, one solution is the application of groundwater resources for irrigation, especially in newly reclaimed land. However, ameliorating the negative impacts of salinity on the soils and crop yield is a priority.

The adverse effects of salinity on soil health and the consequent inhibition of crop growth are well-established. An abundance of literature is available describing how saline soil reduces agricultural crop growth compared to normal expected yields. Moreover, the current scientific literature has introduced the negative consequences of irrigating soils with saline groundwater, including soil deflocculation and dispersion, reduced hydraulic conductivity, and increased ion toxicity. Numerous scientific reports have looked at the varying degrees of impacts of salinity stress on crops—from the early stages of plant germination to the final stage of maturity—caused by salinity in the root zones and its effects on the water and nutrients transported and the roots' architectural traits. However, there is an emerging interest in understanding the interaction of salt-affected soils with mixed irrigation water and crop stress physiology. It is essential to rigorously investigate the alleviating effects of using fresh and mixed irrigation water on crop growth in saline desert soils.

In this regard, many studies have suggested soil amendments to reduce the negative effects of salinity and sustain the target crop production levels. Soil amendments can be considered as a cost-effective option in regions where only saline irrigation water is available or freshwater availability for drainage is limited. In this context, previous studies have encouraged the use of biochar as an organic soil amendment to improve crop yields in salt-affected soils. However, the underlying mechanisms by which biochar improves agricultural yield in saline soils are still unknown. It has also been reported that the application of biochar has adverse effects—e.g., a potential increase in soil salinity, degradation of soil hydraulic properties, and risks to public health and the environment—depending on the application conditions. Thus, further investigation of the short- and long-term effects of biochar in various application conditions on the soil quality, crop yield, public health, economic factors, and environment is required for planning a desert agricultural system with soil amendments. The results of these investigations will help establish the proper and standardized use of biochar with saline water irrigation systems.

Reclaiming desert lands for agriculture with saline groundwater irrigation and soil amendments can contribute to improving food security in Egypt. However, its planning and implementation are complicated, due to the complex feedback interactions and uncertainty associated with a number of components, including irrigation water availability, infrastructure conditions, soil types and condition, and crop productivity within agricultural systems under dynamic climate and socioeconomic changes. In this context, we identified the feedback processes for the irrigation water, infrastructure, soil, and crop productivity sectors, which interact within the reclaimed desert agricultural systems. Understanding these interactions is the key to describing how a change (e.g., increase or reduction) in a component (e.g., saline groundwater irrigation) or driver (e.g., climate change) can lead to a change in other components (e.g., Nile River water availability) as a result of their causal relationships. Systems thinking based on the feedback processes has successfully tackled the challenges of using saline groundwater with or without soil amendments in agricultural production in arid regions.

Planning a sustainable desert agricultural system requires developing the inherent feedback interactions in ways to achieve target crop production levels and minimize social, economic, and environmental impacts. In this sense, systems thinking also helps to explore the insights and strategies needed to achieve sustainable desert agriculture under the impacts of dynamic drivers—i.e., system-dynamics-based decision models, irrigation systems with diversified and decentralized water sources, the incorporation of urban water demand management, sufficient energy availability, smart irrigation systems, and active participation of stakeholders.

There have been a few review studies that have investigated soil salinity effects, saline water irrigation, and soil amendments on reclaiming agricultural land. However, few attempts have been made to discuss the challenges of achieving sustainable desert agriculture with a systems thinking approach. In this context, the discussions and insights in this study will be used to encourage current and future agricultural stakeholders, including academic communities, to employ a systems approach in the development of advanced, quantitative, and systematic decision-making frameworks appropriate for sustainable desert agriculture systems.

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