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Toward a Greener Future: Applying Circular Economy Principles to Saudi Arabia's Food Sector for Environmental Sustainability

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Abstract: Applying new designs and business formats to production and consumption patterns as part of the circular economy (CE), an increasingly popular concept within environmental research, ensures sustainable food production practices and fosters environmental sustainability. The CE approach is particularly relevant in arid regions, such as the Kingdom of Saudi Arabia (KSA), challenged by extremely harsh climates where natural resources are both scarce and excessively exploited. This study thus aims to show how the CE concept can be applied to the food sector in the KSA by identifying relevant issues and related CE strategies through a literature review. The CE framework is presented to explain sectoral challenges at the macro and meso levels and maps the associated circular strategies with specific models and corresponding examples of industrial applications in. Finally, circular strategies from the mapping are compared with the current situation in the country to identify where they are already practiced, identify gaps and priorities, and outline prospects. Effective management of food loss and waste requires a timely, holistic strategy to add value to the sustainable development goals (SDGs) outlined in the Saudi Arabia Vision 2030 and SDG 12.3 target that aims to reduce the rates of food loss and waste by 50% by 2030.

Keywords: circular economy; food sector; food losses and waste; sustainability; responsible consumption

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1. Introduction

Food loss and waste (FLW) has become a global concern, with approximately one-third of the food produced for human consumption being lost or discarded [1]. In 2019, global food waste was estimated to be 931 million tons, of which household waste accounted for almost 570 million tons (61.2%) [2]. As of 2021, over 828 million people globally are undernourished and experience hunger, and the number of undernourished individuals are increasing [3]. The consequences of the COVID-19 pandemic are expected to worsen the world food crisis [4]. In addition, the UN's forecast that the world's population will surpass 8.5 billion people in 2023 and 9.8 billion people by 2050, along with an increase in emerging nations' incomes, will drive up food consumption further. By 2050, it is thought that 70% more food will be required than the amount consumed today [1–3].

Food waste is not only a bad habit that adds to the world's yearly production of over 1.3 billion tons of waste, but rather wasted foods cause the production of up to 3.3 billion tons of greenhouse gases (GHGs) [5], particularly methane emissions [6]. Indeed, 8–10% of human GHG emissions are caused by worldwide FLW [7], and recent research [8] found that GHGs from rotting and other discarded food make up around half of all emissions from the global food chain. Food waste is also responsible for economic loss and the depletion of scarce resources, including land, water, and energy, used in the cultivation, processing, and distribution of food and results in the loss of life-sustaining nutrition and severe financial losses for both individuals and national economies [9].

To address these global issues, FLW must be incorporated into urban planning for sustainable development to meet the requirements of the Sustainable Development Goals

(SDGs) and a circular economy (CE) [10]. Urban planners have a unique opportunity to manage growing populations and build communities that promote sustainable food systems. Urban planning may help create sustainable food systems that reduce waste and encourage the reuse and recycling of food sources. Several SDGs support food waste management in urban planning, such as eradicating poverty (SDG 1), decreasing inequality (SDG 10), promoting universal well-being (SDG 3), guaranteeing sustainable patterns of consumption and production (SDG 12), and battling climate change (SDG 13) [10]. Moreover, cities can contribute to SDG 2 (zero hunger) by distributing extra food and reducing food waste. Thus, achieving the SDGs and transitioning to a CE depend on minimizing food waste via effective urban planning.

The CE is based on the principles of minimum waste and maximum resource efficiency, and the CE concept arose from the need to protect and preserve limited natural resources. In the past, societies tended to take and use materials without considering the consequences of their disposal. In the CE, these consequences are considered, and strategies are taken to minimize potential hazards. The concept refers to integrating economic activities and environmental well-being sustainably. The primary focus is on redesigning material cycling and processing and increasing ecosystem functioning and human well-being [11]. Thus, the CE stimulates growth by conserving resources [12] and addressing resource scarcity and waste disposal by extracting economic value from waste [13]. As the CE offers sustainability, governments are encouraging, and in some cases mandating, the adoption of CE principles and practices [14].

The concept of "closing the loops" in places with an arid climate rest on using economic models that encourage recycling and reuse [15]. Thus, CE initiatives implement environmentally beneficial practices, such as using recyclable packaging and maintaining a focus on green products; they also minimize energy consumption, waste production, adverse environmental effects, and dematerialization [16]. As the CE is based on "closing the loops", it therefore offers a chance to move away from the linear model, which produces a great deal of waste and carbon emissions, and toward a low-waste, zero-carbon economy [17].

The CE reduces the amount of garbage that ends up in landfills through the reuse, recycling, and recovery of material. In contrast, the linear economy model produces garbage that harms the environment and human health [18]. According to Milios [19], the CE concept combines traditional ideas of resource efficiency with the explicit discussion of the financial benefits of resource conservation. Ultimately, it aims to replace a linear pattern of production and consumption known as "take-make-waste" with a sustainable system that increases the value of resources, materials, and products [20].

In recent years, the CE has become more important to politicians, businesses, and academic institutions. Policymakers promote a CE approach through regional and national policies, especially in the European Union (EU) and China [21]. The European Green Deal, which aims at climate neutrality, is of particular note, as one of its policies involves transitioning the economy from a linear to a circular model to address waste production, including the food sector to reduce environmental degradation.

Therefore, the current research examines how the CE can be adopted in the KSA's food supply sector, which includes agriculture, manufacturing, food processing, and distribution. This sector functions as a complex industry that encompasses a diverse and global network of businesses that supply most of the food consumed by the world's population, making it both a significant driver of waste and a potential source of sustainability.

Using the food sector to illustrate the CE provides opportunities to advance the concept and investigate its potential. The novelty of the current paper lies in its examination of an aspect that has received little attention in the CE literature. It offers a case study of how CE principles can be applied to the food sector in the KSA and thus contributes to the larger conversation on CE practices in regional contexts. Moreover, it introduces a framework that integrates a CE and supply chain management concepts to foster a more sustainable food sector in the KSA where, according to current data, food waste

is an extensive issue with a substantial social and economic impact [22–24]. Specifically, this paper outlines how a CE approach can be adopted in the food sector in the KSA by exploring the issues, strategies, regulations, and execution challenges encountered in the KSA as a descriptive case. Conceptually, this paper adds to the scholarly literature by further mapping the frameworks of CE issues and policies. It also provides case reports demonstrating ideal regulations for supply sectors. The following research questions have therefore been formulated to guide the research: what issues are raised and what CE strategies can be adopted within the food sector in the KSA, and how can the KSA apply the CE framework effectively?

The upcoming section provides a review of the literature on the CE in a fundamental supply sector, followed by Section 3, which outlines the research methodology. Section 4 introduces the suggested CE framework and its circular strategies, detailing their implementation at macro, meso, and micro levels in the context of KSA's food sector. In Section 5, the focus is on prioritizing and outlining future pathways for a CE in the food sector, starting from the initial mapping exercise to potential circular strategies. This paper is concluded in Section 6, which summarizes the findings and suggests directions for future research.

2. Literature Review

The CE concept originated in the commercial and production industries [25–27], after which the idea of sustainability of the food and water sectors was taken up. The literature reveals multiple investigations of the CE and its impact on society, undertaken in various circumstances and at different levels, regions, and sectors. For example, Del Borghi et al. [28] found that the CE contributed greatly to recovering the supply of energy and mineral resources in the Netherlands. Specifically, other studies [29,30] concluded, more generally, that CE practices greatly encouraged the reduction in food waste, energy conservation, and other green activities at the same time.

Franceschelli et al. [31] contended that as environmental and social considerations are crucial parts of operating a business, the food sector needs to establish innovative sustainable business models, and an array of models. They highlighted that technological advances associated with the CE have been studied. The input–output model, for example, was utilized to investigate resource-use efficiency in the Australian food industry as a component of the CE [32]. Donner et al. [33] explored the elements of circular business models for agricultural waste, while Hamam et al. [34] systematically reviewed CE models in agri-food systems.

The main subject matter of CE-related research articles involving the basic food supply is food waste, as this is the primary field in which the CE can be employed. A study carried out in 2016 projected that annual food waste costs in the US would rise from USD 13 billion to USD 17.5 billion by 2020 [35]. Food waste results in the needless use of resources, which fuels overuse, pollution, and high energy consumption. Slorach et al. [36], Vilariño et al. [37], and Ingrao et al. [38] explored several technologies in connection to food waste, while Jurgilevich et al. [39] evaluated the challenges and socio-technical developments surrounding the CE in the food sector. Voulvoulis [15] and Abu-Ghunmi et al. [40] argued that to fully appreciate the importance of a CE in the basic food supply, an in-depth and rigorous investigation must be conducted.

Before considering how the CE literature can be applied to the KSA, the area studied in this paper, it is necessary to understand some background and the country's unique circumstances. Nine decades after oil was found, the KSA has seen fast expansion, urbanization, and economic prosperity. The prevailing linear economic paradigm, in which ever-increasing quantities of raw resources are extracted, processed, and made into goods that are eventually thrown away, has been increasingly challenged over the past few years due to its unsustainable nature. The KSA could instead adopt a CE approach centered on maximizing the value and sustainable use of resources while eliminating waste. The CE model is a necessity and not a luxury for this region. Thus, the focus of this case study is on the KSA, which has considerably depleted its already scarce supply of fresh water

and agricultural land using extensive agriculture, urbanization, and dependence on waste disposal facilities. It also has some of the highest levels of pollution in the world and is more vulnerable to climate change than several nations [41,42]. Economically speaking, the nation must move away from oil and develop other non-oil industries with plentiful employment opportunities, including those offered by the CE. The KSA is among the extremely arid regions in which a CE would be significantly impactful [43,44] and has an acute need for a sustainable food supply, considering its extreme climatic conditions. The country is one of the hottest and driest countries in the Gulf region and, indeed, the world; water scarcity, high temperatures, and low rainfall have caused extremely limited agricultural activities [45,46]. Moreover, the water scarcity caused by climatic conditions has been exacerbated by the excessive exploitation of groundwater aquifers throughout the entire Middle East [47].

The KSA is classified by the United Nations [48] as a developing but high-income country and is one of the world's top food importers. The scarcity of natural resources has caused food dependency, decreased domestic crop production, and a deteriorating climate [49]. The food chain is centered on distribution and consumption, and the role of food production is insignificant. In most developing countries, food waste occurs within the food chain as it is challenging to preserve and transport food before it spoils. In contrast, in high-income countries, the spoilage happens at the consumer and retailer end of the food chain, and this is the situation that occurs in the KSA [50]. Although the KSA is the largest country in the Middle Eastern region, it has the least arable land per capita (0.114 ha/capita) and only 1,736,472 km^2 of the total agricultural land [51]. The population has increased by 43%, making the situation critical and putting even more pressure on the food supply. According to predictions by the World Bank [51,52], 46 million people will need food by 2050. Most food waste in the KSA is landfilled, which raises GHG emissions from decomposition. In addition, the poor state of the landfills exacerbates environmental problems.

Therefore, a comprehensive framework to synchronize CE applications across various stakeholders in the KSA, encompassing consumers, government entities, and businesses, and to generate value at the macro, meso, and micro levels is required for effective implementation of the CE in the KSA. Despite the pressing need for innovative solutions to boost local food production in the KSA, limited academic research has delved into efforts to apply CE principles within the country's food sector. This study endeavors to bridge this gap by presenting an original framework for CE applications in the KSA's food supply sector.

3. Materials and Methods

This study focuses on the KSA as an example to illustrate how the CE concept is used in the food industry. It creates a framework model to identify challenges and initiatives related to the CE that apply to fundamental supply sectors. By analyzing value chain and circular strategies of the food sector, multiple industrial applications of the CE concept will be identified and described. The main activities involved in local food production will serve as examples of the variety of applications. Our methodological approach is presented in this section together with a selection of case studies, the identification and characterization of CE indicators, and techniques for measuring the CE in the KSA's food sector.

3.1. Framework for Evaluating Supply Chain Circularity in the KSA's Food Sector

The model presented in this research is based on the synthesis of the CE developed by Kirchherr et al. [53], which integrates the results of interviews and a thorough analysis of the elements that CE definitions should include. Additionally, the current research adapts the "6R" (reduce, reuse, recycle, recover, remanufacture, and redesign, organized by priority) approach to the CE developed by Jawahir and Bradley [54], which provides a CE value chain and identifies potential loops within the food value chain (Figure 1). The value chain analyzed in this research is limited to five primary stages, namely, extraction, processing, manufacturing, use, and disposal, all relevant to food production.

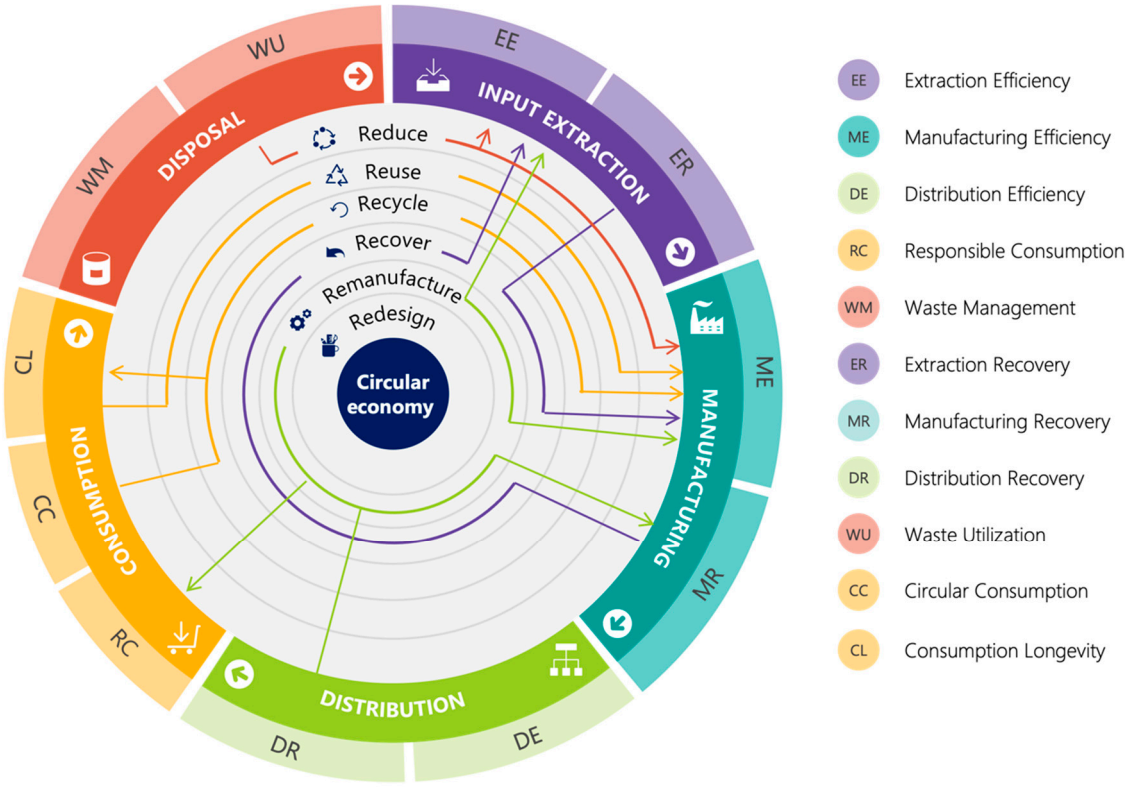

Figure 1. The 6R CE framework in the supply chain and circular strategy loops in the food sector (adapted and modified from [44]).

According to Kirchherr et al. [53], the CE has four principal objectives. Firstly, it aims for environmental quality, to protect the environment from human interference, and to preserve it via sustainable business activities. Secondly, it seeks to generate economic prosperity and growth without compromising environmental quality. Thirdly, it targets social equity, focusing on the well-being of the community. Lastly, it aims to meet the needs of future generations by considering the long-term temporal dimension. Along with these four objectives are three systems or perspectives that are required in an all-inclusive approach that focuses on three systems: the micro system (company and customer level), meso system (local and eco-industrial level), and macro system (national or global level).

It is essential to define, break down, and then reassemble the CE into workable methods to map it out in the food sector. This paper aims to provide a comprehensive foundation for further studies on the adoption of CE strategies in natural resource management, with a particular emphasis on the food sector as a crucial basic supply sector. Previous studies, for example, have used bibliometric analysis as a model but gathered data only on food waste and CE trends and patterns [55] or examined the introduction of circularity concepts into food waste management [56]. In contrast, the present study conducts a detailed analysis of the CE model, which includes all of the value chain steps adopted in the food sector and CE principles, to generate strategies that can address food security issues in the KSA and similar countries. By mapping major themes and research gaps, this research can help managers and policymakers in the KSA make the shift from the traditional linear to a CE-based food industry.

3.2. Circular Strategies and Frameworks

The circular strategies considered in this study align with the 6R principles and connect the various stages of the value chain through specific loops to develop a business model tailored to the food sector. Figure 1 visually represents these circular strategy loops. For example, the extraction step is associated with reduction and recovery. In this step,

the extraction or procurement of raw material is reduced or recovered, and the process thus becomes sustainable and can be minimized through reuse and recycling. In the same manner, the manufacturing step is interlinked with reduction, reuse, and redesign, while the distribution step is interlinked with reduction and recovery (reducing distances and intermediaries and recovering the supply chain). The consumption step value chain is associated with the three Rs: reduce, recover, and reuse. Finally, the disposal step is associated with reducing and recovering waste and improving the waste management process.

In recent years, several innovative extraction techniques have been developed, ensuring the production of sustainable ingredients for food. These methods include extrusion; mechanochemistry; high pressure, ohmic, UV, and IR heating; microwaves; ultrasound; electric pulse fields; instantaneous controlled pressure drop; and sub- and super-critical fluid processing [57]. Green food manufacturing is associated with minimizing energy use for food manufacturing or processing and water use in the harvesting and washing process. Advanced food production technologies help save resources and improve food quality compared to conventional food production processes [58]. Efficient and sustainable food distribution is possible through an efficient transportation management system that will help reduce carbon emissions and improve the bottom line. Environmentally sustainable food consumption has been discussed by Veremeir et al. [59], who found that many people have positive attitudes toward green food consumption. However, there is a significant gap between attitudes and actual food purchasing decisions. Consuming food that meets basic needs and improves the quality of life while reducing the use of natural resources, toxic materials, waste, and pollution emissions throughout their lifecycles to protect future generations' needs is known as environmentally friendly food consumption [60]. In short, all of these steps can be combined to build a sustainable food system by encouraging synergy between humans and nature [61]. Table 1 elucidates each of these circular strategies by delving into the core economic principles that underlie them and their connections with the Rs. The mapping, which features all five value chain steps identified as applicable to food supply sector, was carried out according to the CE synthesis developed by Kirchherr et al. [53] with the 6R principles outlined previously. These CE principles were then utilized for the respective value chain step and their significance within the food sector. This detailed analysis of the CE model, including all of the value chain steps adopted in the food sector and how each 6R principle can underpin strategies to address the KSA's food security, enables a more coherent understanding of the CE concept, its adaptability within the region, how it can be implemented, and its significance.

Table 1. Detailed analysis of the CE model.

Value Chain Steps	Perspectives	Circular Economy Principle	Strategy Description	Significance in the Food Sector
Extraction	Efficiency Recovery	Reduce Recover	Reducing input during the extraction process and procuring raw materials sustainably. Recovering product from raw materials.	Farmland is extremely scarce in the KSA. The crucial fossil fuels for food production are gas, power generators, and oil. Agricultural input is land, water, seed, implement, and fertilizer. Sustainability can be attained using renewable energy sources, such as solar and saline water. Retrieval of food products from soil. Using the land simultaneously for different purposes with multiple agricultural techniques.

Table 1. *Cont.*

Value Chain Steps	Perspectives	Circular Economy Principle	Strategy Description	Significance in the Food Sector
Manufacturing	Efficiency Recovery	Reduce Recover Redesign Remanufacture Recycle	Reducing the input during food production. Recovering and preserving food from being dumped in the bin. Redesigning manufacturing processes and equipment. Remanufacturing and thus reducing waste. Using recycled products in manufacturing.	Increasing food production efficiency through vertical farming; integrated terrestrial and marine systems; hydroponics and aquaponics; smart (sensor-based) greenhouses; sustainable soil intensification; enhanced crop diversity; improved plant control; and enhanced insect management [49]. Using recycled material for fresh production. Use of wastewater.
Distribution	Efficiency Recovery	Reduce Recover Redesign	Reducing transportation damages. Recovering distribution losses. Redesigning distribution processes to make them more efficient.	Reducing fuel use during transportation. Using digital technology, artificial intelligence, supply chain sensors, sophisticated food containers, etc.
Consumption	Responsibility Circularity Longevity	Reduce	Reducing the consumption of natural resources through proper planning and management. Using and making an essential amount of food.	Spreading awareness through social media and other media campaigning, education, and celebrity endorsement. Self-evaluation through footprint calculations and other such apps.
Disposal	Waste food management and waste utilization.	Reuse Recycle Recover	Reusing food for animal feed. Reusing good (unspoiled) food for people in need. Recycling waste material; recovering and reusing useful material from it.	Designing and executing SMART (specific, measurable, achievable, relevant, and timely) strategies.

4. Results

This section of the paper describes the food industry in the KSA from the macro, meso, and micro perspectives using the CE supply chain model. Furthermore, it examines the effects of circular strategies on sustainable growth during the shift toward a CE. Subsequently, examples are given of industrial implementations of circular approaches within the food sector.

4.1. Mapping a Possible CE in the Saudi Food Sector

Compared to previous research, such as by Jurgilevich et al. [39] that addressed the CE in the food supply chain and examined difficulties and socio-technical changes, the results of the present research were based on issue mapping from the CE framework, which enabled deeper exploration of the food sector issues and challenges faced by the KSA. Developing countries, such as the KSA, face several challenges when adopting CE food supply practices. First, there is an urgent need to integrate scarce natural resources, including renewable (agricultural land, forests, seafood resources, livestock, etc.) and non-renewable (e.g., fossil fuels and mineral substances) resources. These resources are components of extended systems [62] and must therefore be used with the utmost responsibility. Attaining sustainability through a CE is vital, especially in countries such as the KSA, where natural resources are extremely scarce. Like other Gulf Cooperation Council (GCC) countries, the

KSA relies on imports to satisfy its food demand. An average of 80% of the KSA's food needs are fulfilled through import activities [63,64], and only 20% is produced locally [65]. Local food production is constrained by several natural factors, such as the harsh and extreme climate, water scarcity, and lack of good-quality land [66]. The Saudi government stopped producing wheat between 2008 and 2016 [67,68], which reduced the country's self-sufficiency in food. The KSA's reliance on imported food products will remain high, especially essential commodities, such as cereal grains [69–71]. The significant growth of the tourism sector has led to a greater food demand as tourism is a food-intensive sector. Therefore, as it has become imperative to procure food without depleting existing resources, the CE principle must be adopted in the KSA to meet the needs of current and future generations.

Furthermore, understanding the macro, meso, and micro levels of the CE enables a better understanding of the leading issues and applications that would best support the CE transition at different levels. According to Al-Saidi et al. [44], at the macro level, the food sector should be analyzed in terms of its capacity for sustainable development and environmental conservation. The supply chain sector should also be improved through proper policies and ecologically focused regulations, including the strategic use of ultra-modern and sophisticated technologies and net-zero carbon emission targets. At the meso level, a challenge is posed by two key issues. The first is the spatial differentiation of food products (farmland, vertical farming, urban farming, and terrestrial and marine systems), and the second is the product differentiation of food (vegetables, seafood, forage, poultry products, etc.) and resource reuse issues. The promising solution to address these two issues in food is to use sources such as saline water or wastewater or to reuse water.

4.2. Current Directions for CE Application

4.2.1. Food Waste Issues in the KSA and Recycling and Conversion of Food to Reduce Waste

One of the key measures that need to be addressed when adopting a CE in the KSA is food waste, because it endangers the country's food security. Baig, Al-Zahrani, and Schneider's [72] research works demonstrated that every week, 78% of the food purchased in the KSA is thrown away to make way for more goods. This finding is supported by Baig et al. [73], who stated that with 427 kg of food wasted per capita per year, the country ranks among the top food wasters. The KSA is also experiencing the depletion of non-renewable aquifers, the primary reason for which its unsustainable food procurement and farming practices [72]. In addition, food waste has adversely impacted the environment as it is the main contributor to landfills [74]. Indeed, contribution to landfills is one of the most urgent issues to address in the KSA, which is due to poor management practices, lack of support from the government, and lack of social awareness of the need to reduce food waste [75,76]. In 2014, 15 million tons (about 75%) of municipal solid waste (MSW) was generated in the KSA. The amount of food waste will double by 2033 if it is not managed properly [77]. In the major cities like Jeddah, Riyad, and Dammam, more than 6.7 million tons of waste are generated annually [78]. Massive food waste has also been reported in the religious cities Makkah and Medina, which are visited by millions of pilgrims for Hajj [79–82].

It should be noted that massive amounts of food are wasted in the KSA even though local food production is inadequate. Baig et al. [72] further stated that food waste continues to be one of the main problems endangering KSA's food security. Although there are no exact scientific estimates of food waste from food service establishments, supply chains, or families, the KSA leads the world in food waste, according to the Ministry of Environment, Water, and Agriculture's (MEWA's) most current report [83]. According to the research by the Saudi Grains Organization (SAGO) [84], the Saudi Minister [23] claims that around 33% of food, valued at roughly SAR 40.4 billion (USD 10.77 billion), is wasted annually. While the global average amounts to approximately 115 kg, the average food waste per capita in the KSA is 427 kg annually. Numerous studies emphasize how much food is thrown out at weddings, banquets, food service establishments, and hotel feasts. Abdullah et al. [85], for

example, identify that dinner hosts' behaviors, society's lack of awareness concerning food waste, and the propensity to show off expensive dishes for guests are the main reasons for food waste in the KSA. Moreover, operations that can reduce food waste in hotels and restaurants are frequently disorganized [86], and there are currently no regulations in KSA to restrict or eliminate food waste.

According to the range of estimates presented in Table 2, Saudi Arabians waste around 1.3 kg of food daily, or around 470 kg annually, amounting to food waste of USD 35 million per day, or USD 13 billion annually [35]. The place of residence is where almost half of this garbage is generated. Furthermore, waste travels in the supply chain and occurs primarily at the commercial and individual levels in middle-class and high-income nations [87]. Although rice is one of the main products linked to food security in KSA [88], Saudi Arabians discard between 35% and 40% of their cooked rice annually, worth around SAR 1.6 billion [82].

Table 2. An overview of the amounts of food waste estimated for KSA.

Source	Estimate	Data Source for Estimate
FAO, G [87]	210 kg/cap/yr (food loss and waste; North Africa and West and Central Asia).	Literature search and information from local FAO offices/universities; assumptions and estimates based on comparable places/commodities/supply chain stages.
COMCEC [89]	119 kg/cap/yr (household). 733 kg/establishment/year (food service).	Self-report survey of 111 consumers and 94 food service establishments in Riyadh.
GAS [90]	14,220,000 metric tons of household solid waste/yr. This is equivalent to 458.5 kg/cap/yr of household solid waste. If this is 36% food, then food waste = 165.1 kg/cap/yr.	
Saab, Tolba [91]	1.5 kg/cap/day of solid waste (equivalent to 547.5 kg/cap/yr of solid waste). If this is 36% food, then food waste = 197.1 kg/cap/yr.	Solid waste analysis in cities such as Riyadh, Doha, and Abu Dhabi.
Khan and Kaneesamkandi [92]	5.5 million tons/yr.	Solid waste experts reported that solid waste collected in KSA could contain 50.57% food.
Al-Saif [93]	28% of Saudi waste is food. 1.2–1.4 kg of food waste/person/day (511 kg/capita/yr).	N/A
Ministry of Environment, Water, and Agriculture [94]	250 kg/cap/yr.	N/A
Gazette [95]	1/3 cooked food.	N/A
BCFN [96]	427 kg/cap/yr.	Estimate from Eta'am (Food Bank) director.
Al-Fawaz, N [97]	Over 50% of food is wasted. Over 70% of food from public events is wasted	N/A

Source: [98].

Table 3 outlines the estimated percentages of food loss and waste (FLW) relative to the availability of different food groups at various stages in the supply chain [99]. In 2016, the KSA experienced a total FLW rate of 33.1%, of which food waste constituted 18.9% and food loss 14.2%; vegetables and fruits saw the highest rates of FLW, at 39.5% and 39.6%, respectively [99]. The economic impact of this FLW is estimated at approximately SAR 13 billion [99]. On a per capita basis, FLW amounts to 184 kg/year, with vegetables and fruits showing equally significant per capita waste figures [96]. Alshabanat [96] indicates that substantial FLW in commodities such as wheat, rice, fish, poultry, and red meats occurs at the consumption stage. In contrast, for vegetables and fruits, the production phase and,

to a smaller degree, the consumption phase, see the greatest levels of FLW. Therefore, it is crucial to explore new and innovative technologies and sustainable alternatives for food production, such as smart horticulture.

Table 3. Estimated FLW as a percentage of available food.

Products	Loss	Waste	Total FLW	Value (Millions of Riyals)	FLW (kg/Capita)
Wheat	5.0%	24.7%	29.7%	912.57	27.61
Rice	3.0%	30.6%	33.6%	1682.46	16.77
Dates	15.6%	5.8%	21.4%	588.05	4.12
Fish	18.5%	14.5%	32.9%	493.50	2.09
Poultry	13.1%	15.9%	29.1%	3407.97	13.39
All vegetables	24.5%	14.9%	39.5%	3407.97	30.87
Potatoes	27.8%	14.1%	41.9%	372.40	6.00
Carrots	16.1%	14.5%	30.6%	46.80	0.80
Zucchini	25.6%	15.4%	41.0%	74.20	1.10
Cucumber	25.8%	16.7%	42.5%	260.00	2.00
Onions	8.4%	17.2%	25.6%	167.00	3.50
Tomatoes	23.1%	16.5%	39.6%	428.50	8.00
Unclassified vegetables	27.5%	16.1%	43.6%	1252.00	10.00
All fruits	24.3%	15.3%	39.6%	2733.767	25.35
Watermelon	32.0%	9.0%	41.0%	253.90	4.62
Mango	16.90%	9.40%	26.3%	42.26	0.36
Orange	14.50%	13.50%	28.0%	180.65	3.07
Unclassified fruits	22.50%	17.50%	40.0%	2257.00	18.00
Meats	16.40%	14.90%	31.3%	576.30	2.30
Sheep	6.80%	7.70%	14.5%	401.40	0.65
Beef	23.80%	19.30%	43.1%	618.70	1.30
Camel	14.50%	19.70%	34.2%	149.70	0.40
All products	14.20%	18.90%	33.10%	20,307.097	184

Source: [99]. Note: USD 1 = SAR 3.75.

4.2.2. Campaigning for Reducing Food Waste

The KSA has started implementing initiatives toward minimizing food waste by imposing certain regulations on hotels to reduce food waste [100]. However, a personal and commercial approach needs to be developed to reduce this problem. Tarik Ismail, the executive director of Savola Group, a well-known Saudi food giant, said that there has to be a cultural shift in how people see food waste; for example, food conservation is seen as a sign of hospitality in Arab culture [101]. Educational programs are being conducted at schools to increase awareness among young people of the importance of food conservation and healthy eating. The need for a healthy diet is also promoted to reduce health problems among the new generation [101].

4.2.3. Conversion and Recycling of Food Waste

Several studies addressing the adverse impacts of food waste in the linear food production system have stated that this system results in massive amounts of food waste being disposed of in landfills, which is the most unsustainable disposal process and has adverse environmental impacts, such as GHG emissions and climate change [102]. Furthermore,

apart from the humanitarian implications of wasting food, the country has to bear the costs of farming, harvesting, transporting, packaging, and preparing food that is ultimately thrown away [103]. It is further supported by the emission of CO_2 and disruption of the entire food supply chain. Considering the alarming food waste situation in the KSA, the circular production process is necessary for converting and recycling food waste.

Food can be produced using highly sophisticated and eco-friendly technologies. There should be an efficient system for and management of recycling food to produce value-added products from it. For example, biofertilizers can reduce the use of chemical fertilizers and, consequently, environmental pollution while supporting the CE [104]. The KSA has already taken steps to reduce food waste, including cutting back on food consumption, gathering leftover food and giving it to those in need, and turning food waste into animal feed [105]. The practice of feeding food scraps to animals has long been prevalent in the KSA, where surplus food is often fed to chickens, goats, and sheep.

Salemdeeb et al. [106] stated that it contributes to lowering costs as well as adverse effects on the environment. Food preservation was emphasized in the KSA's Vision 2030 as a moral commitment and priority. To reduce food waste, investments in waste management as well as educating the agricultural market have been undertaken [107]. Food waste consists of hydrocarbons and is subject to a variety of thermochemical reactions. Sustainable and economical methods can be employed to recover, recycle, and reuse food. For example, Elkhalifa et al. [108] and Alaboudi [109] proposed using biochar and biofertilizers to improve the soil and showed how a variety of techniques can be employed to collect, recycle, and utilize wasted food. Another increasingly common method of processing and managing food waste is recycling waste cooking oil (WCO), which is an appealing option due to its reasonable price and environmental friendliness [81,110,111].

Dates, a primary fruit in the country, offer another CE opportunity. The KSA's goal for Vision 2030 is to become the world's biggest exporter of dates, although it currently produces 539,755 tons of dates each year, 184,000 tons of which are exported, generating SAR 860 million in income [112]. Residents may distribute waste dates to animals, while date oil may also be extracted and transformed into biodiesel [113].

The Saudi food bank Eta'am, operated by the Al Fozan Foundation, is taking the initiative to spread awareness about responsible use of food and avoiding food waste through conventional and digital media. Their interventions include animated short films for children and teachers and spreading the message among tourists about the need to preserve food [95]. Eta'am is also working in collaboration with the Dow KSA company to develop a school program to spread awareness among children about the importance of preserving food and the negative impacts of food waste [114]. Around 3000 volunteers are involved in various activities, such as collecting food from restaurants, schools, institutions, wedding halls, and other such places, storing it in refrigerators, packaging it properly, and distributing it to those in need [82,115,116].

Another food preservation solution, developed by a Saudi citizen, is a plate with a central bump to reduce rice waste by 25%. Many restaurants used it, and it was sold across the GCC region [117]. At the legislative level, a fine is imposed for food waste that is equal to 38% of the bill per serving [117]. Jeddah, where 60% of municipal waste is waste food, is proactively supporting a CE by preserving food: around 900 containers have been placed throughout the city to collect waste food and redistribute it among the poor [118]. Like Jeddah, the Riyadh Municipality is experimenting with food recycling through the "City without Containers" program, where households in the city are required to use the two-bin system to separate organic waste from other waste so that it can be composted instead of dumped in landfills [119]. Thus, composting is a common waste management activity in the KSA.

5. Discussion

The presented model and the literature expanded on in the Results section demonstrate the necessity of CE adoption in the KSA and its relevance to the country's environmental

sustainability and economic development. Previous studies in this field have various aspects of the CE concept [120], including the perspectives of citizens, as revealed via surveys [121,122], and the trends and patterns of a CE in the food sector [55]. Nevertheless, the current paper is novel in that it features a KSA-specific CE model, mapping out issues in the KSA's food sector and presenting CE strategies that managers, policymakers, and even households can adopt. Whereas other researchers have mainly explored the CE concept, its effects, and its efficiency [29,32,37,38], our research has proposed a comprehensive framework that synchronizes applications across various stakeholders, encompassing consumers, government entities, and businesses, and generates value at the macro, meso, and micro levels. Despite the pressing need for innovative solutions to boost local food production in the KSA, limited academic research has delved into efforts to apply CE principles within the country's food sector. This study has bridged the research gap by presenting an original framework for CE applications in the KSA's food supply sector. To expand this discussion, the following subsections discuss the KSA's current situation and how a CE can be achieved in the KSA through applications in the food sector.

5.1. The KSA's Current Condition for a Circular Economy

The KSA is the largest country in the Gulf region, with an area of 2,149,690 km^2 [123], and it occupies approximately 80% of the Arab region [124]. It has a population of approximately 30.77 million people, as of 2020, according to the Ministry of Economy and Planning [125]. However, it has one of the harshest and most arid climates in the world, making farming and food production challenging.

Though industries are the major drivers of any economy, the agricultural sector cannot be overlooked when a country's economic growth is concerned. A country's self-reliance in food production is crucial to avoid risks like dependency on imports and food security issues [126]. Considering the dry and extreme climate of the KSA, conventional crops, such as wheat, barley, sorghum, and millet, are not viable options for farming. As noted previously, when the KSA government paused wheat production in 2008 for eight years, wheat also had to be imported. As a staple food, importing wheat is costly and puts significant pressure on the country's expenditure [127]. To bridge the gap between actual food needs and food availability in the KSA, it is crucial to focus on sustainable agriculture research to utilize natural resources sustainably and take the country toward self-reliance in food production. The KSA's CE goal is aligned with that of the European Green Deal, which seeks to reduce pollution, reverse biodiversity loss, halt climate change, and promote the effective use of resources by establishing a sustainable CE. The KSA can follow some of the European Green Deal action plans and take both legislative and non-legislative actions aimed at areas in which regional action brings real added value. It can also follow the European Green Deal's lead in terms of how it targets product development, promotes CE operations, advocates sustainable consumption, and seeks guarantees that waste does not accumulate and the resources utilized are kept within the economy for as long as possible.

The main subject of discussion in this study is the concept of a CE in the food industry in the KSA. The primary goal of putting the CE into practice is to highlight the advantages of extracting, recycling, reusing, and sustainably disposing of food products. Most garbage in landfills is food waste [119], which also plays a part in causing environmental harm, such as climate change through methane emission. The three most populous cities in KSA—Dammam, Riyadh, and Jeddah—produce half of the country's waste [128]. The biggest contributor to food waste is the hotel industry, followed by celebrations and events [129]. Three significant studies in this regard have suggested various technologies. For example, composting helps to increase soil fertility and attain sustainability in food production, and there is evidence that the KSA has achieved a net saving of about USD 70.72 million per year through this method [86]. In addition, anaerobic digestion is a cost-effective technology, especially when dealing with large amounts of food waste. Evidence from the KSA shows that it has high efficiency with a low annual cost of USD 0.1–0.14/ton [69]. Cumulative net savings from landfill waste diversion are SAR 256 to 533 million. The carbon credit of the

technology is SAR 46 to 96 million, while the fuel savings are SAR 46 to 96 million. Finally, SAR 273 to 569 million's worth of electricity is generated through this technology in the KSA [130].

According to the Economist Intelligence Unit [131], the KSA lacks strong and formal legislation on the national CE strategy. Although the kingdom has adopted several environmental policies and legislation in recent years, it is still challenging to control the conventional linear process of the food cycle.

5.2. Vertical Farming to Implement the CE in the KSA

Against a background of land scarcity, urbanization, and ecological issues, cities must deal with the problem of the space required for the cultivation of food crops. Cities lack the space to contribute to the agricultural sector. However, vertical farming has created opportunities for cities to grow plants by using abandoned residential buildings, factories, warehouses, and so forth.

Recently, the KSA has begun vertical farming initiatives to conserve water, increase food production, and boost food security. Moreover, implementing a CE through vertical farming is suitable for the KSA, because 82% of the population live in urban areas [45], and vertical farming gives a wide range of customized options to adapt to a specific climate. As the primary renewable energy source available in the KSA is sunlight, large solar panels can support vertical farms. They can be installed near farms and deliver energy to them at a low cost. Some plants need more energy, while some plants can be grown with less; accordingly, species that need more sunlight can be placed on the floor to receive it, and additional light can be provided by installing lighting.

Vertical farming has immense potential to produce a significant amount of food for local communities and will be the ideal option to deal with the challenge of climate change and scarce water resources. Moreover, it provides a self-sustaining solution, as it is based on local rather than foreign resources. It is also sustainable, as it can meet the food needs of both current and future generations. To meet the increased demand for food, the KSA needs to be self-reliant, and by adopting vertical farming practices now, it will be at the forefront of developing large-scale vertical farming. Vertical farming can be carried out in every possible urban area to make cities self-reliant. Locally grown food products will minimize transportation costs and environmental losses that occur in supply chain activities and require less extraction of natural resources than conventional farming. It will also create manufacturing jobs, improve distribution efficiency and recovery, and be a creative step toward attaining CE goals.

5.3. Sustainable Food Production

As discussed earlier in Tables 2 and 3, the KSA experiences food scarcity and food waste issues and, like other GCC regions, has to rely on imported food because local production is insufficient.

The collaboration between King Abdul Aziz City for Science and Technology (KACST) and the Tanmiah Food Group is a step forward in sustainable food production development through a CE. It aims to develop innovative and advanced technologies to reduce the harmful impact of poultry production and thus minimize or eliminate carbon footprints during production and within the supply chain. Efforts are also being made to bridge the gap between industry and research bodies in the CE [132], primarily in terms of reduction, reuse, recycling, recovery, redesign, and remanufacture, to bring the CE into reality. The CE will be possible in a real sense in the KSA by increasing local food production and, at the same time, putting minimal pressure on locally available natural resources.

Water is essential to food production; hence, in applying the CE to the food sector, the KSA's goal will be to achieve food and water availability and security [133–135]. The country has already applied a wide range of strategies, but these efforts are not adequate. Table 1 presents various strategies and their significance for every value chain and R principle. As some of these strategies may be challenging or not cost-effective, further research

and exploration are essential to examine their viability and practicality, especially in terms of realizing Saudi Vision 2030. A proper legal framework and its effective implementation are the most critical factors in successfully adopting a CE in the Saudi food sector, which is why relevant policies and legislation should be strengthened.

Waste management strategies need to be more explicit and interlinked. Figure 1 indicates how every principle, value chain step, and strategy is linked. Thus, food waste management policies must be all-inclusive to maintain a CE. Waste in the GCC region, including the KSA, occurs in the forms of household, industrial solid, hazardous material, and medical waste [136]. Recycling waste material (food in our research context) will help reduce pollution and landfill issues [137].

Efforts at the local and national levels are critical in organizing, implementing, and managing CE strategies. The present research suggests attainable, relevant, and achievable strategies that need to be supported by advanced technologies. Therefore, support from local and national governments and organizations is essential. However, it is observed from the extensive literature review that the KSA still lacks a CE agenda. Therefore, an effective agenda with appropriate strategies and urgent actions is crucial. Furthermore, to attain the goals of a CE in the food sector, long-term investment is essential.

KSA can reduce waste in the food supply if legislative and political initiatives are taken. However, legislation regarding awareness, waste management, and the acceptability of by-products is currently missing [76]. Moreover, food is wasted at lavish celebrations and festivals. There should be a statutory framework for reducing food waste, such as enforcing fines, imposing self-disposal, a statutory prohibition on certain food wastage, and emphasizing waste segregation.

However, relying on laws and statutory mandates is not sufficient. Along with government entities and other public- and private-sector bodies, it is the responsibility of every individual to participate in the CE by avoiding food waste. Awareness of the extra pressure placed on limited natural resources, especially in the KSA, when food is wasted should be spread among individuals. Wasting food also means wasting labor, financial investment, and all kinds of resources. Therefore, individual efforts should also be considered among the primary components of the CE. It is every citizen's responsibility to reduce food waste by adopting a healthier and more sustainable diet and avoiding excessive food purchases. Public awareness of the CE in the food sector should be spread actively.

The government can also encourage ordinary individuals to develop ideas about appropriate food management from extraction and manufacturing to disposal. Baig et al. [72] made eight recommendations aligned with the CE. First, approaches and interventions should be formed and implemented, and second, data should be collected and research carried out on the CE and its appropriate application. Thereafter, it is necessary to build awareness among people through campaigns, after which food recovery and recycling should be promoted by strengthening the food bank concept and providing incentives for donations. Policies should be developed to reduce food consumption and facilitate all food supply steps (e.g., extraction, manufacturing, distribution, consumption, and disposal). The waste management and food waste reduction practices of both businesses and consumers should be shifted. Next, proper food systems should be built, and education campaigns should be run for ordinary people, shopkeepers, and people working in the food sector.

6. Conclusions

6.1. Brief Summary of the Results and Their Significance

The KSA, a country in the Gulf region with extreme climatic conditions, including high temperatures and arid land, has an acute scarcity of natural resources. Sustainability in food production is the only way to deal with the issue of natural resources, and the CE has become the KSA's most effective option. Closing the gap between the available and required resources is possible only through applying the principles of reduce, recycle, reuse, recover, redesign, and remanufacture (6R) to food waste. Value chain reorganization will help the country attain sustainability in resource uses. However, the KSA still lacks an

effective framework for this purpose and is the largest food waste generator in the world. Globally, the CE is primarily adopted in manufacturing sectors; however, in KSA, the food supply sector is crucial to attaining sustainability goals, and an agenda for sustainability needs to be developed. The UN General Assembly has already adopted a sustainable development agenda aimed at the "transformation of our world" toward a fairer and more peaceful future [138]. Aligning with the UN's goals, the KSA's agenda should include conserving the ecosystem, reducing carbon and GHG emissions, and curbing its ecological footprint. As of 2019, the country's per capita CO_2 emissions were 14.62 metric tons, while its ecological footprint in 2023 was 5.77 global hectares per person, which denotes the impacts of human activities on the environment measured by quantifying natural resource consumption per capita [139].

It is necessary to adopt CE principles to alleviate the environmental and resource issues in the KSA. The present research provided a CE framework in which every component is closely related and which includes primary value chain steps, such as extraction, manufacturing, distribution, consumption, and disposal, and considers the 6Rs. All of these steps are primary activities in the basic food supply. This framework applied multi-level supply system viewpoints and widely accepted CE ideas to integrate and rearrange the fundamental supply value chain. The mapping effort produced circular strategies which contain a wide range of workable examples to improve the food industry's adoption of the CE. This article also discussed some broad CE concerns at the macro and meso levels and made recommendations for waste reduction and the conversion and recycling of food waste.

6.2. Theoretical and Practical Implications

This paper has made some recommendations for the successful design and implementation of the CE. There is an acute need for economic food policies aligned with the CE. Some important strategies for achieving the CE suggested in this paper include input reduction in the extraction process, as it is the initial step in food production from which sustainability must start [140]. Sustainable procurement of raw materials for food is crucial. In this regard, the viability and efficacy of vertical farming in the KSA should be assessed, especially with the Saudi Vision 2030 target of total recycling of wastewater generated in urban areas [140]. The second strategy is recovery, that is, preventing the maximum amount of food from being thrown away. As food waste is a serious problem in the KSA, the recovery strategy is critical. The redesigning strategy is related more to the overall food system than any single food. The system should follow a CE model to prevent waste production. Remanufacturing strategies have already been introduced in European nations, and the necessary equipment is available. However, the market has not yet been developed. The KSA food sector can consider the equipment for remanufacturing and refurbishing food. Applying these practical recommendations can significantly aid in the KSA's goal of adopting a CE and achieving its sustainability goals.

6.3. Limitations and Future Research Directions

Mapping the CE is crucial to the successful implementation of the investigated economic approach. However, the Gulf countries, including the KSA, still lack CE mappings, such as the effective adoption and promotion of waste management, public awareness, and active participation. In addition, recycling and recovery strategies need extensive research, which the KSA still lacks. Such research will help find solutions to unsustainable food production and environmental problems. Research is a long-term project because it is time-consuming and requires extensive financial, technological, and human resources. Considering the need for sustainable food practices, the Saudi government should invest in research and development on the effectiveness of a CE in the food sector. Conducting research is a highly complicated process that should be carried out in collaboration among various stakeholders, such as community members, researchers, governments, NGOs, and other private- and public-sector bodies. There should also be appropriate policies

and statutory provisions for implementing a CE. For example, China and some European nations have already designed policies directed toward achieving a global commitment toward sustainability. The KSA can study and review the food sector's CE policies of these countries and design policies that will be suitable and relevant for the economic, social, cultural, and geographic aspects of the KSA, which should be explored in future research.

There is no issue-based institutional framework in the KSA. Therefore, the food sector's performance depends on the policymaking process and approach of the concerned authorities. The primary targets for cost-cutting are poor food waste management, food security and its governance, the infancy of vertical farming, and resources. Cross-sectional regulations will help address the cost-cutting issues. Infrastructure investment is also hugely important in attaining a CE in the food sector, and the infrastructure for food processing, packaging, quality control, trade centers, and transportation needs to be sustainable. A highly advanced infrastructure also needs to be developed near landfills for reusing, recovering, and recycling waste food. Another limitation of this study that could be addressed by future research is that it did not explore how the CE could be applied in other relevant sectors, such as water and energy. Nevertheless, this study has significantly underscored the relevance, adaptability, and importance of utilizing a CE in supporting sustainability goals, including food waste reduction.

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