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Research article

Circular Economy in Basic Supply: Framing the Approach for the Water and Food Sectors of the Gulf Cooperation Council Countries

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ABSTRACT

The circular economy concept can enhance sustainability through restructuring consumption and production patterns using innovative designs and business models. This core premise is highly relevant for the interlinked water and food supply sectors in arid regions, which are threatened by natural scarcity and resource overuse. This paper transfers the idea of the circular economy into the practice of the water and food sectors using the example of the region of the Gulf Cooperation Council (GCC). It develops a framework for identifying circular economy strategies and issues applicable to basic supply sectors. In analyzing the value chain and circular strategies of the water and food sectors, the circular economy idea has resulted in numerous industrial applications. The range of applications is illustrated in the key industries of wastewater and local food production. Expanding the reuse options for municipal wastewater and valorizing organic waste represent important circular economy directions for the basic supply sector of the GCC. Incorporating these ideas is positive, but a more comprehensive set of measures is needed to generate low-carbon and low-metabolism economic development in the region. In addition to the current sporadic supply-side initiatives, there is a need for non-technical circular economy strategies related to demand management and waste reduction.

1. Introduction

The basic premise of the circular economy centers around restructuring both consumption and production patterns towards a low-metabolism and low-carbon future. This idea can be achieved through different applications in different regions, with the overall aim of enhancing the circulation of products and consumer awareness. In arid parts of the world, the most concerning pressures are those on water and arable land resources. Without conservation and efficient use, growing economies and populations can cause resource scarcity. The circular economy idea of 'closing the loops' through business models fostering reuse and recycling can be quite relevant for such arid regions (Voulvoulis, 2018). It is heralded as a way of saving resources and stimulating growth (Stahel, 2016). Other circular economy notions are those of slowing (i.e., the expansion of a product's lifespan) or narrowing (i.e., resource-use efficiency) the loops through business models and design strategies supported by policymakers (Bocken et al., 2016). In economics, the circular economy has been around since the early 1990s as a way of capturing the total functions of the environment and applying principles of accounting for external effects (i.e., negative impacts or externalities in economic activities) (Andersen, 2007). Several other ideas of industrial ecology, cradle-to-cradle, or steady-state economy are closely related to the circular economy (Kalmykova et al., 2018). At the same time, aligned to the circular economy are ideas of strong sustainability and degrowth, since they all advocate changing the business-as-usual mentality and lowering societal metabolism (Schröder et al., 2019).

Lately, policymakers have been promoting these ideas under the banner of circular economies through national or regional policies, most prominently in China and the European Union (Geng and Doberstein, 2008; McDowall et al., 2017). The bulk of interventions are in the manufacturing industry (Lieder and Rashid, 2016). Product design or business model innovations to enhance the circular economy exist in other industries; e.g., product-service systems or waste industries (Singh and Ordoñez, 2016; Hernandez, 2019; Kjaer et al., 2019). There are, however, few applications of circular economy concepts in the basic supply sectors such as the water, energy, infrastructure, and agricultural sectors. Particularly in developing regions of the world, these sectors are typically infrastructure-heavy, under strong public control, and not exposed to a high throughput of innovations. Nonetheless, they are highly important for reducing ecological footprints and environmental externalities. In arid regions such as that of the Gulf Cooperation

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Council (GCC), the circular economy concept could be highly relevant. In this paper, we examine how the circular economy translates into the reality of key supply sectors, namely the water and food sectors.

The concretization of the concept of the circular economy for the water and food sectors offers opportunities to develop this concept further and explore its potential. With this in mind, this paper focuses on how to break down the idea of the circular economy in the context of the basic supply sectors such as the water and food sectors. As previously stated, the circular economy concept is poorly understood with regard to basic supply, with very limited case studies in this area. The paper aims to develop a novel framework for framing the circular economy approach for the water and food sectors. Using the GCC region as an illustrative case for the potential of the circular economy concept, the paper lays out issues, strategies, directions, and implementation challenges. It contributes to both the conceptual academic literature, by seeking the development of adequate mapping frameworks for circular economy issues and strategies, and the case study literature, by showcasing exemplary directions for the supply sectors. First, a short review of the circular economy in basic supply is provided, and the paper's relevance reiterated. Second, the original circular economy framework is introduced and related circular strategies are mapped along with respective examples. Using this framework, the overall sectoral issues on the macro and meso levels are explained, and later, concrete examples of business models and industrial applications are provided from the GCC region. Finally, prioritizations and future directions for the Gulf region are discussed by contrasting the current status with other examples of conceivable circular strategies from the initial mapping exercise.

2. Literature review

The circular economy concept originally emerged out of industrial or manufacturing applications (Geng and Doberstein, 2008; Bocken et al., 2016; Lieder and Rashid, 2016; Geng et al., 2019), but it has since found ground in other industries related to the supply of basic amenities such as food and clean water. Broad applications to the water and food supply sectors focus on showcasing the relevance of the circular economy to the environmental objectives of these sectors and other related sectors such as health and energy. For example, Del Borghi et al. (2020) focused on the contribution of the recovery of energy and raw materials to the circular economy in Netherlands, while van Leeuwen et al. (2018) argued that the circular economy through life cycle thinking could lower environmental impacts across the water-energy-food nexus. Other studies presented the wide range of benefits from circular economy applications such as food waste utilization (Slorach et al., 2019) or from the different technologies in the areas of waste management, energy and water management and green strategies in general (van Fan et al., 2019).

Alongside these broad studies on the environmental benefits, there are applications targeting single technologies, selected industries or specific subsectors in the water and food sectors. For example, life cycle assessments have been used to highlight the design, applications and benefits of the circular economy for water tourism in Northern Europe (Strazza et al., 2015; Scheepens et al., 2016). Other applications of the circular economy include the promotion of lean practices in small and medium water companies in Europe (Sartal et al., 2020), and of sewer mining in Greece (Makropoulos et al., 2018). Another example is the use of input-output models to analyze resource-use efficiency in sub-areas of the agri-food industry in Australia as an element of the circular economy in basic supply (Pagotto and Halog, 2016).

For the basic supply sectors, the main two issues highlighted in the academic literature are food waste and loss as well as the reuse of wastewater. First, food loss and waste have been highlighted as key areas for applying the circular economy idea. Several studies have listed viable technologies and expected environmental benefits related to food waste reduction and utilization (Vilariño et al., 2017; Ingrao et al., 2018; Slorach et al., 2019). For the case of Italy, Principato et al. (2019) quantified food waste and loss for the pasta industry, while Borrello et al. (2017) designed an experiment to gauge the consumers' preferences on reducing food waste. Second, with regard to wastewater utilization, studies utilizing the circular economy concept have shown the challenges facing the expansion of water reuse (e.g., regulatory, health, environmental, or public acceptance issues) (Voulvoulis, 2018; Guerra-Rodríguez et al., 2020). There have also been case studies showcasing experiences in tackling these challenges in Europe (Smol et al., 2020), India (Kakwani and Kalbar, 2020), or Spain (Hagenvoort et al., 2019). Wastewater treatment as a part of the circular economy concept has also been highlighted in several projects focusing on treatment technologies of wastewater for the extraction of biofuels in Europe (Bianco, 2018; Paul et al., 2018).

Altogether, the current literature linking the circular economy to the basic supply sectors focus on discussing general environmental benefits and on analyzing specific issues (e.g., food waste or water reuse) or subsectors (e.g., food manufacturing or water-based recreation). There have been few sector-wide studies of the food or water sectors. For example, Jurgilevich et al. (2016) discussed the circular economy in the food sector from the lens of socio-technical transitions, and presented some challenges. Fassio and Tecco (2019) linked the circular economy in the food sector to the Sustainable Development Goals (SDGs) through a description of contributions and issues. Esposito et al. (2020) provided a literature review linking the circular economy to the agri-food sector. They highlighted the complexity of perceptions of the circular economy and the relevance of this concept for achieving overarching sustainability goals. In the water sector, Sgroi et al. (2018) reviewed studies on the feasibility and sustainability of water reuse and discussed how the circular economy can promote this reuse. These sector-wide studies are often not driven by a specific framework or definition of the circular economy, while the applications are not regional and mostly focus on one sector. The paper at hand responds to this gap since it provides a systematized narrative of the circular economy in several basic supply sectors using the GCC region as a case study. Its original framework can be used for mapping applications across the value chains and the circular economy principles.

In order to showcase the potential of the circular economy for basic supply, it is relevant to provide more holistic and systematic assessments, particularly from regions with harsh climatic conditions (Abu-Ghunmi et al., 2016; Voulvoulis, 2018). Considering its natural scarcity of water and arable land, the GCC region is in serious need of sustainability approaches focusing on resource efficiency, reuse, and recycling. This region includes countries with similar climatic and economic conditions, and exhibits a rare form of institutionalized (environmental) cooperation among states in the Middle East shaped by political turmoil and changing alliances (Al-Saidi, 2020). The member countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE)) are rich in carbon-based resources. However, they are undergoing a tangible modernization, mainly in the built environment, in order to reduce their large carbon footprints (Al-Saidi and Elagib, 2018). Besides this, they are becoming more engaged with the global sustainability agenda (Al-Saidi et al., 2019). The circular economy concept is advocated for the region as a way of making cities more sustainable through the recycling of materials, efficiency measures, and waste management (Strategyand, 2019). However, other than singular examinations of reuse options, e.g., water reuse in GCC countries (Aleisa and Al-Zubari, 2017; Zubari et al., 2017;

Brown et al., 2018; Al-Saidi and Dehnavi, 2020) and the use of waste to produce biofuels in Saudi Arabia (Rehan et al., 2018), there is no academic work detailing circular economy efforts in the region. Moreover, a study of circular economy-based contributions to enhancing the sustainability of the key supply sectors (water, land, and energy) would be quite valuable considering the lack of studies in this area and the relevance of these sectors. The water and food supply sectors present bottlenecks for achieving sustainable development in this arid region. The region is characterized by very high water scarcity and overuse of vulnerable groundwater aquifers (Saif et al., 2014; Zubari et al., 2017). As a result, GCC countries need to find alternative resources and technologies to complement desalination and enhance local food production (Brown et al., 2018). The interlinkages between such sectors are becoming increasingly important. Water and food production need to incorporate energy-efficient technologies, water reuse options, renewables, and risk management strategies (Abulibdeh et al., 2019; Al-Saidi and Saliba, 2019). Mapping the circular economy applications for the water and food sectors is a crucial step in the understanding of sustainability options for these key sectors.

The exercise of mapping the circular economy in the water and food sectors requires the defining and breaking up of this concept, and later reconstructing it into tangible strategies. Responding to this demand for systematic and structured analysis, and considering the above-mentioned relevance of the circular economy for resource-scarce regions, this paper seeks to provide a holistic picture as a basis for future research into the development of circular economy strategies in natural resource management, with a focus on the water and food sectors as two key basic supply sectors. Mapping the circular economy issues for the water and food sectors is a challenging but valuable exercise considering the resource-use priorities in the Gulf. In fact, the circular economy has several meanings and relationships in common with other sustainability paradigms and the sustainable development concept in general (Geissdoerfer et al., 2017; Korhonen et al., 2018). Since its emergence as a sustainability paradigm, this concept has had different connotations, but the main emphasis has been more on the transformation of businesses and industries and less on social issues of sustainability (Murray et al., 2017). In our framework (Section 3), this core focus is maintained, as we map circular economy issues across the value chain of resource-supply production and highlight industrial examples. Analyzing value chains and businesses has been a main theme in the circular economy literature. For example, Pishchulov et al. (2018) reviewed the literature on closed-loop supply chain management and supply chain design, coordination, and operation. Here, the underlying supply chain is embedded in four elements related to natural resources: extraction/preparation, production (including distribution), consumption (including markets), and waste management. Similarly, Kalmykova et al. (2018) defined a value chain in a circular economy by breaking down the value chain into seven main steps (materials, design, manufacturing, distribution and sales, consumption and use, collection and disposal, and recycling and recovery) while incorporating a couple of loops among the different parts of the value chain.

3. Methods

3.1. Framework development and value chain description

We limit our value chain (see Fig. 1) to the five core steps (input extraction, manufacturing, distribution, consumption, and disposal) most relevant for supply resource production (i.e., water and food supply). Here, the product design step is not relevant, since most water and food products are homogenous or have a certain required baseline quality. In order to fill in the value chain with circular economy contents and define the possible loops, we rely on the circular economy synthesis developed by Kirchherr et al. (2017), based on an extensive review of necessary components in definitions of the circular economy. Accordingly, a comprehensive understanding of the circular economy needs to include the 4R principles (Reduce, Reuse, Recycle and Recover), which are ordered by a priority rank (i.e., first reduce, then reuse, etc.). We use these core principles for identifying loops across the value chain and defining subordinate or synonymous principles. For example, the Reuse principle includes (and is sometimes the same as) other principles mentioned in the literature (Fig. 1).

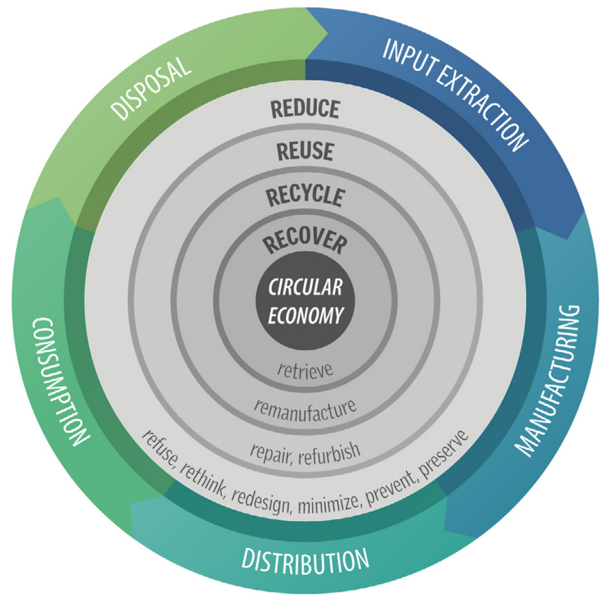

Fig. 1. Circular economy framework: value chain and principles.

According to Kirchherr et al. (2017), comprehensive definitions of the circular economy need to refer to sustainable development by stating the four aims of (1) 'environmental quality' (i.e., environmental protection and restoration); (2) 'economic prosperity' (i.e., improving economic outcomes); (3) 'social equity' (i.e., focusing on well-being); and (4) 'future generation' (i.e., a long-term temporal dimension). In addition, the circular economy definition has to incorporate three systems perspectives to be understood and applied in a holistic way, namely (1) a micro-systems perspective (i.e., the firm and consumers level); (2) a meso–systems perspective (i.e., the regional or eco-industrial level); and (3) a macro-systems level (i.e., the global or national level). In our analysis of the water and food supply sectors, the analysis units for the three perspectives are presented in Table 1. In this paper, the macro-level perspective takes in the water and food supply sectors, while the meso level is applied to the wastewater plant or farming system. In Section 3, we focus on the macro and meso levels and map circular economy issues for the water and food sectors in the GCC countries using the framework depicted in Fig. 1. We also discuss the manifestations of the four above-mentioned aims of sustainable development through a shift towards the circular economy in these sectors. In Section 4, we focus on the micro level and present concrete industrial and business examples using the circular strategies explained in the following section.

3.2. Circular strategies and business models

In order to structure our illustration of business models, we connect the value-chain steps and the 4R principles through certain loops we evaluate as being viable for natural resource-supply

Table 1
Analysis units in the different circular economy perspectives.

Systems perspective	Macro level	Meso level	Micro level
Analysis Units	National-level sectors, industries	Sub-industries and production plants	Products, business models, and consumer preferences
Water Sector	Water supply and treatment sectors	Wastewater plants	Wastewater-related products, alternative water use in agriculture
Food Sector	Food production sector	Food industries	Food waste utilization in several applications

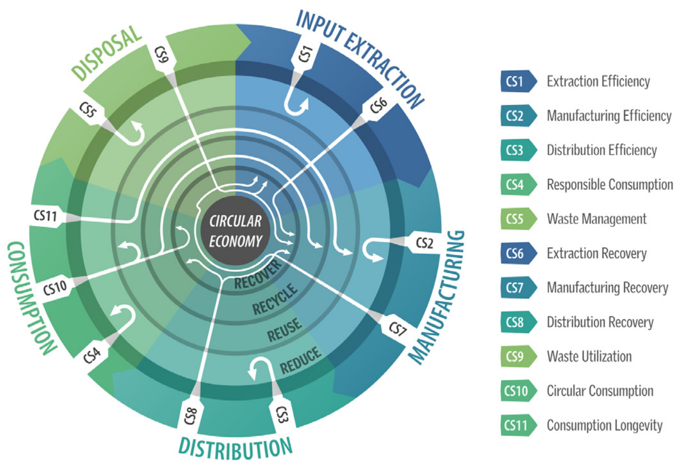

Fig. 2. Loops between value-chain steps as circular strategies.

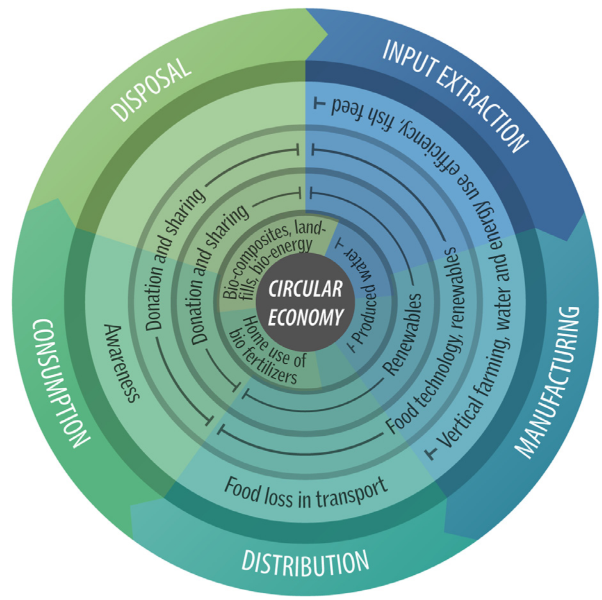

Fig. 3. Issue mapping in the food sector.

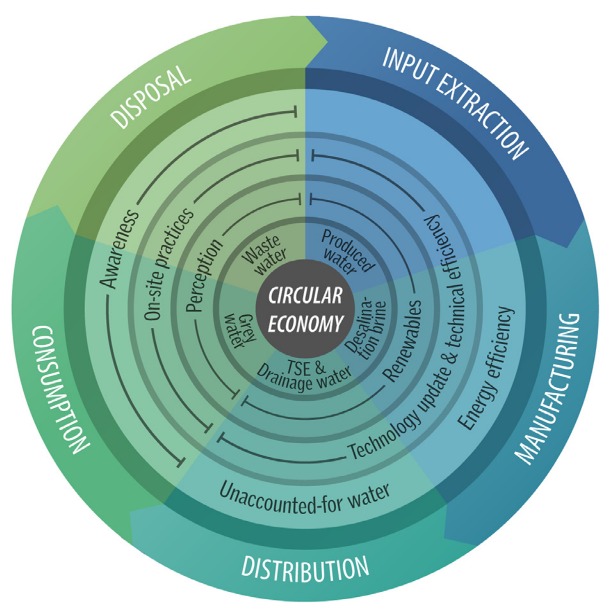

Fig. 4. Issue mapping in the water sector.

sectors. These connections/loops are depicted in Fig. 2, and we call them 'circular strategies' (CSs). For example, CS 6 relates to recovering materials for the input extraction step and reintroducing them in the manufacturing step. As such, the CSs represent the value-chain directions (e.g., from input extraction to manufacturing) and the circular economy principle (e.g., recovery). In this sense, they include the spatial characterizations of the loops without revealing the exact business model.

Table 2 explains these CSs based on the main economic concept behind them. For example, reducing input use in the manufacturing step is essentially technical or manufacturing efficiency. Furthermore, the business models represent the manner in which a firm is doing business. The role of business models in the circular economy has been extensively reviewed by Geissdoerfer et al. (2018) and Bocken et al. (2016). Accordingly, the aims of circular business models can vary; e.g., closing (through recycling), slowing (product life extension), narrowing (efficiency improvement), intensifying (increased intensity in use through sharing, for example), and dematerializing (substitutions through services and software) the loops. Our CSs do not incorporate these aims *per se* but can be categorized under one or more of these loop types (Table 2). There are many examples of circular business models described in the literature, such as sharing and leasing schemes, recycling companies (e.g., in the car and electronic industries), and waste management ideas. However, there are few presented in the literature with regard to the water and food value chains. This paper is concerned with these models. They will be presented in Section 4 as cases of business models but also as industrial examples, i.e., applications that are yet to be introduced on a commercial scale but are suitable for such an introduction (Section 4.2). Section 4.1 provides an initial mapping of macro- and meso–level issues in the GCC region based on the previously introduced value chain framework of the circular economy.

4. Results

4.1. Mapping overarching circular economy issues

The circular economy issues in the water and food sectors in the GCC region are mapped in Figs. 3 and 4. While some issues such as distribution losses, renewables, technology, and efficiency

Table 2
Analysis units in the different circular economy perspectives.

No.	Circular strategy	Circular economy principle	Value chain steps/loop direction	Type of loop (using the classification in (Geissdoerfer et al., 2018)	Strategy description	Significance and examples for water and food sectors
CS1	Extraction Efficiency	Reduce	Input extraction	Narrowing	'Reduce the input during the extraction of the input/raw materials', meaning how to provide sustainable or sustainably produced raw materials required for manufacturing/ production.	• Input or raw materials needed for water and food production are typically arable land, water and fertilizers for food production; and energy and chemicals for water production • The most relevant inputs for producing these raw materials are fossil fuels (e.g., petroleum products for synthetic fertilizers, gas for power generation, etc.); water, land/space are the most relevant inputs for farming land; proteins and oils are required for fish production. • Sustainable alternatives: use of bio-fertilizers; incorporation of renewable energy sources such as solar farming and desalination; vertical farming; use of marginal water (e.g., saline water) for food production; use of alternative fish feed
CS2	Manufacturing Efficiency	Reduce	Manufacturing	Narrowing; dematerializing; intensifying	Reduce the input required for water and food production.	• Efficiency measures in water production include more energy-efficient membrane technologies; more efficient pumping systems; automation. • Efficiency measures in food production include vertical farming; combined terrestrial and marine systems; hydroponics; aquaponics; smart (sensor-based) greenhouses; sustainable intensification of soil; crop variety improvements; plant control; improved pest management.
CS3	Distribution Efficiency	Reduce	Distribution	Narrowing	Reduce losses during transportation.	• Reduction in food losses during transport through intelligent systems (e.g., high-tech containers), post-harvest treatment, supply-chain sensors, better logistical services, etc. • Reduction in unaccounted-for water (UFW) (i.e., non-revenue water (NRW)) through maintenance of networks and better monitoring systems (e.g., metering or smart systems)
CS4	Responsible Consumption	Reduce	Consumption	Narrowing; intensifying; dematerializing	Reduce consumption.	• Mostly awareness-raising measures such as nudging, media campaigns, education, and role models; self-accounting systems (e.g., apps for consumption and footprint calculations, detailed bills), etc.
CS5	Waste Management	Reduce	Disposal	Narrowing; dematerializing	Reduce waste in post-consumption phases.	• Development of comprehensive waste management strategies for segregation, landfill management, infrastructure, etc. • Linking awareness-raising on consumption to waste management policies
CS6	Extraction Recovery	Recover	From input extraction to manufacturing	Closing	Recover useful materials (suitable for industrial applications) from the extraction of input materials.	• Retrieval of materials based on the type of input: e.g., utilization of produced water (a by-product of energy production); water algae from water for several purposes • Retrieval of several products from soil/land during preparation for food production; multi-purpose use of land such as co-location of renewables and food production, or through several agroforestry techniques

(*continued on next page*)

Table 2 (*continued*)

No.	Circular strategy	Circular economy principle	Value chain steps/loop direction	Type of loop (using the classification in (Geissdoerfer et al., 2018)	Strategy description	Significance and examples for water and food sectors
CS7	Manufacturing Recovery	Recover	From manufacturing to input extraction	Closing	Recover useful materials during production as input for other products.	• In water production, utilization of brine water during desalination • In food production, utilization of drainage water, and harvest losses, e.g., for ecosystems remediation, fuel production, etc.
CS8	Distribution Recovery	Recover	From distribution to consumption	Closing; slowing	Recover distribution losses for consumption or industrial purposes.	• Donation of unsold food of good quality; use of food waste during the distribution for biofuels; diversion of collected water losses in the network for purposes such as landscaping
			From distribution to manufacturing	Closing		
CS9	Waste Utilization	Recover	From disposal to input extraction	Closing	Recover useful materials as raw materials or to be incorporated directly in manufacturing.	• Collection and reuse of treated wastewater effluent (TSE); food waste as biofuels, organic composite, and a source of lipids and protein; several materials retrieved from landfills
		Recover	From disposal to manufacturing	closing		
CS10	Circular Consumption	Reuse	Consumption	Closing; intensifying	Reuse, recycle and recover resources during consumption for consequential use.	• Water-saving and sharing applications in houses; reuse of graywater and food composite on-site; household-level water purification systems; sale of collected household waste to companies
		Recycle	From consumption to manufacturing	closing		
		recover	Consumption	Closing; intensifying		
CS11	Consumption Longevity	reuse	From consumption to manufacturing	Slowing	Extending the life of products	• Use of better food storage techniques in homes; appliances for quality monitoring and improvements in water and food at homes; donations of food to specialized companies or agencies for efficient redistribution

are common concerns for many countries, others related to the reuse of different types of water and the reduction of energy and land requirements are particularly important for dry regions. It is becoming evident that more integration and circulation of resources is urgently required. Furthermore, as earlier stated, comprehensive circular economy analyses need to relate to the overarching objectives of sustainable development (Kirchherr et al., 2017). This is especially important for the water and food sectors as they are vital for sustainability, supply security and economic welfare in the arid Gulf region. For example, the deterioration of groundwater quality and quantity is a major protection challenge that affects the prosperity and livelihood of future generations. This deterioration is due to demand growth and unsustainable use. Between 2010 and 2018, population growth in GCC countries ranged between 13% (UAE) and 58% (Oman) (FAOSTAT, 2019). This is in addition to remarkable economic growth as well as the expansion of food-intensive sectors such as tourism. Although all GCC countries are considered food-secure, they still rely on imports to satisfy the increasing food demand (Harrigan, 2014). The food imports not only cover the food supply ready for consumption but also the ingredients required for local food production (Yaqoob, 2011). Local food production is, however, limited by several factors, including the harsh climate, the dry land, the poor soil quality, and the water scarcity (Shahid and Al-Shankiti, 2013). Therefore, securing a basic supply of affordable food and water services without depleting the limited natural resources represents a major challenge in the Gulf region. Such a task has immediate implications not only for the livelihoods of the current generation, but also for the welfare of future generations.

In reviewing circular economy issues, we differentiate between the macro and the meso levels. At the macro level, circular economy in the water and food sectors needs to be examined with regard to its potential contribution to fulfilling the overarching goals of environmental protection, economic prosperity, livelihood improvements, and intergenerational justice. At the national level, water and food policies need to promote water conservation, acceptance and awareness of water reuse, as well as the integrated regulation of water and related issues (Saif et al., 2014). Furthermore, the transformation of the supply sectors in the region should be framed within broader policies of ecological modernization through renewables, technologies, and low-carbon measures (Al-Saidi and Elagib, 2018), or the quest to adapt to risks from a global environmental force such as climate change (Al-Maamary et al., 2017; Al-Saidi and Saliba, 2019). At the meso level of industries and production plants, there are two overarching circular economic issues. First, food production is becoming more differentiated both spatially (i.e., conventional farms, urban agriculture, vertical farming, combinations of terrestrial and marine systems, etc.), and in terms of products (i.e., from fish, vegetables, forage, or other high-value products such as fish feed or biofertilizers). Secondly, water use and reuse issues are becoming more comprehensive (i.e., the utilization of many water types) to meet different demands, including food production. This entails utilizing lesser-used sources such as saline water, wastewater, or on-site collection and reuse (Aleisa and Al-Zubari, 2017; Brown et al., 2018).

4.2. Current directions for business models and industrial applications

4.2.1. Multipurpose utilization of municipal wastewater

The utilization of municipal wastewater is one of the most pressing topics in the Gulf due to its contribution to the augmentation of water supplies and extraction of other resources that can be used in several other manufacturing processes. In general, industrial applications relying on the use of wastewater are in line with the earlier-mentioned circular strategies of waste management (e.g., municipal wastewater as a product of disposal of consumed water resources), extraction recovery or manufacturing recovery (wastewater as a by-product in industry, desalination, or energy production). So far, treated wastewater has been increasingly recognized as an important resource, although the bulk of academic literature in the field promotes its use for agricultural purposes (Aleisa and Al-Zubari, 2017; Brown et al., 2018; Al-Saidi and Dehnavi, 2020). Much of the collected wastewater is still not used either directly (e.g., in agriculture or landscaping) or indirectly (i.e., for extracting materials). This is mainly due to the novelty of this topic in the region, and the current lack of adequate infrastructure and supporting strategies. Table 3 provides some basic statistics on the status quo of wastewater reuse in the region.

With regard to concrete business models and industrial applications exemplifying the concepts of the circular economy, these need to utilize wastewater as a multipurpose resource, i.e., beyond the use of the treated water itself. Due to human activities, various organic and inorganic compounds end up in the wastewater. Depending on the value of the compounds and the process of separation, these compounds could be separated at the place of origin. However, in other cases, these compounds need to be removed by means of microbial consumption, microbial conversion and mineralization, filtration, adsorption, etc., to minimize or prevent environmental pollution. The physical processes of wastewater treatment could be slower and more expensive than biological treatment processes. Municipal wastewater (MWW) represents the bulk of the wastewater for a city – ranging from 30.7 to 442.7 m^3/day/capita (Aleisa and Al-Zubari, 2017). Apart from various organics, MWW typically contains nitrogen (15–90 mg L^{-1}), phosphorus (5–20 mg L^{-1}), and other elements (Cai et al., 2013). Although constructed wetland and microalgae could be used to treat the MWW (Kivaisi, 2001; Das et al., 2019b), the most common practice for treating MWW is the activated sludge process (ASP). During the ASP, the MWW is usually treated through successive processes combining physical, biological, and chemical techniques. Atmospheric nitrogen is converted to ammonia using the Haber-Bosch process, which is energy-intensive. The ammonia formed through this process is mainly used to produce various fertilizers for plant growth (Erisman et al., 2008). The bulk of the nitrogen in the MWW could be linked to the Haber-Bosch process. In this way, recycling the nitrogen from MWW could minimize the requirement for ammonia synthesis, which attributes to greenhouse gas (GHG) emissions. Nevertheless, a fraction of the biosolids generated in the wastewater treatment plants is currently being used in various parts as nutrient-rich fertilizer for the GCC region. For example, in Oman, the sewage sludge is mixed with other green waste (e.g., grass clippings, dry leaves, trimmings from trees and shrubs, etc.) and the mixture is composted using 'windrow' technology. The compost is then used as organic fertilizer (Jaffar Abdul Khaliq et al., 2017). Very recently, according to personal communication with stakeholders, some of the newly constructed wastewater treatment plants in Qatar are distributing the biosolids to the local farmers as soil conditioners. Currently, the world is facing a

Table 3
Wastewater reuse: key facts for the GCC region (in millions of cubic meters (MCM)). Data for the year 2016, adapted from Al-Saidi and Dehnavi (2020).

GCC Country	Wastewater collected (MCM)	Wastewater treated (MCM)	Treated wastewater as% of collected wastewater	Reused water (MCM)	Reused water as% of collected wastewater
Bahrain	158	69	44%	39	25%
Kuwait	319	247	77%	-	-
Oman	68	67	99%	33	49%
Qatar	198	194	98%	97	49%
Saudi Arabia	2503	1604	64%	216	8.6%
UAE	724	711	98%	452	62%
Main uses	Non-edible agriculture for forage cultivation, recharge of groundwater, landscaping and recreation, district cooling, road projects				
Main challenges	Lack of integrated infrastructure, inadequate incentives, distorting freshwater subsidies, lack of promotional policies				

'peak phosphorus' crisis, and it is very critical that phosphorus is recycled whenever possible (Cordell, D., White, S., 2011). The concentration of phosphorus in the MWW is much higher than the requirement for microbial treatment of the MWW. The recovery of phosphorus through struvite formation, as a first process of the overall treatment of MWW, is practiced in some parts of the world (Jaffer et al., 2002). In the GCC, unused treated sewage effluent (TSE) is discharged in the desert for groundwater recharge or disposed of in the sea, whereas the remaining TSE is mostly used for forage production and landscaping and recreational purposes. The presence of residual nutrients in the wastewater treatment could be advantageous over groundwater. Indeed, the yield of sorghum and maize crops in Oman was 30% higher when TSE was used compared to freshwater irrigation (Qureshi, 2020). Construction industries are also utilizing TSE; in the GCC countries, there has been a gradual increase in TSE utilization by these industries. For example, the construction industries in the GCC used 1.5 billion m^3 of TSE in 2015, which was five times higher than their TSE utilization in 1990 (Zubari et al., 2017).

Similarly to MWW, other sources of wastewater (e.g., produced water, industrial wastewater) could also act as a growth medium for producing biomass as feedstock or various bulk chemicals (Das et al., 2019a). Depending on the combination of adopted technologies, the quality of the TSE could vary. Religious beliefs and perceptions about MWW among the direct and end-users often barred the reuse of TSE in many sectors. To expand the use of TSE, some of its constituents such as pathogens, emerging contaminants, and elements of concern need to be removed by appropriate advanced technologies, and even the logistics of collection, storing, and distributing TSE to the respective users needs to be developed (Jasim et al., 2016). Nevertheless, due to the scarcity of freshwater and the environmental consequences of desalination, GCC countries have envisioned the reuse of TSE in the field of fodder production, groundwater recharge, landscaping, industrial cooling, etc. (Zekri et al., 2014; Jasim et al., 2016; Ouda, 2016; Aleisa and Al-Zubari, 2017). In some cases, the generation of TSE could be favored over desalination in terms of cost and energy requirements (Pearce, 2008). TSE often contains residual nitrogen, phosphorus, and other trace elements, and an uncontrolled release or application of TSE could initiate unwanted microalgal growth and consequently pollute the local aquatic ecosystem (a process known as eutrophication) (Glibert, 2007). Instead, selected microalgae could be used to recycle the nutrients and refine the TSE for reuse or discharge to natural water bodies. The biomass generated during the water treatment process could be further processed using a variety of technologies (e.g., anaerobic digestion, hydrothermal liquefaction, pyrolysis, etc.) to generate energy as biogas or biofuel (Das et al., 2020). Furthermore, the techno-economic viability of microalgal bioremediation of wastewater and biofuel production, under Qatari environment conditions, is being studied in a project in the Center for Sustainable Development at Qatar University. The leftover biomass, after extracting the energy, could retain the bulk of the nutrients (N, P, and other microelements) and could be used as biofertilizer. This is in addition to the option of using microalgae-based biofertilizer, which has been shown to be efficient in enhancing the growth of date palm plantlets (Saadaoui et al., 2019).

4.2.2. Alternative water for agricultural production

Due to the large water footprint of local agriculture in the Gulf region, finding alternative water sources is an important policy objective encompassing several research and industrial efforts. There are several circular strategies that can be linked to this objective; e.g., manufacturing efficiency (reuse options of the agricultural water itself); extraction recovery (treatment of water by-products in energy and water production for the use in agriculture); and disposal recovery (e.g., the use of municipal wastewater for agriculture). Industrial applications and business models in this area are also related to important contextual issues of the circular economy, namely, achieving environmental sustainability and intergenerational equity (through preserving groundwater resources), and maintaining the small but important local agriculture sector in the Gulf. Although local agriculture is driving the overuse of groundwater resources, the economic contribution of agriculture and livestock is very low in GCC countries; e.g., 0.2% of GDP in the case of Qatar. Still, local production of essential foods such as vegetables, fruits, and livestock products (meats, milk, and eggs) is extremely important for GCC countries. Table 4 shows the food production patterns among the GCC countries, with Saudi Arabia as the regional leader, followed by Oman, Kuwait, and the UAE. In this context, it is important to look for novel and innovative technologies or sustainable options for food production such as smart agriculture, integrated soil reclamation programs, and non-soil-based production systems. A key issue is to minimize water requirements while producing high-quality products.

With regard to the use of the different types of wastewater for enhancing the circular economy in the region, Al-Saidi and Dehnavi (2020) have provided an overview of current practices and required strategies. For example, more integrated urban systems are needed by linking treatment plants to use sites or advancing vertical farming by using harvested, drained, or treated water. It is important in this regard to have comprehensive strategies that set clear targets for the use of different water types and provide investments in key industrial applications (Al-Saidi and Dehnavi, 2020). For example, hydroponic systems were largely applied in the GCC region and led to a great improvement in the quality and quantity of edible plants produced (Brown et al., 2018). More recently, aquaponics have been applied in the UAE and Qatar as a sustainable and more innovative agricultural production system (Pirani and Arafat, 2016; Abusin and Mandikiana, 2020). In this system, aquaculture and hydroponics are coupled together to produce crops and fish with less water use, less waste, and more benefits compared to both systems applied separately (Blidariu and Grozea, 2011). There are other options for utilizing marginal water (i.e., water of a lower quality). These options, such as combined systems of terrestrial and marine agriculture, and the use of microalgae or produced water for certain products, are systematically reviewed in the GCC case by Brown et al. (2018).

4.2.3. Conversion and recycling of food waste

Tackling food waste in the Gulf is a cross-cutting theme for the circular economy as it accommodates a wide range of the above-mentioned circular strategies. It relates to strategies stressing reducing, reusing and recycling within the value food chain (e.g., manufacturing efficiency, distribution efficiency, responsible consumption, circular consumption, consumption longevity, or waste management) or the recovery of resources for other industrial applications (e.g., waste utilization, manufacturing recovery, distribution recovery). Among the different strategies cited above, improving awareness about food waste reduction, and encouraging food redistribution by private/social organizations as donations to needy people are the most commonly adopted strategies in Saudi Arabia (Baig et al., 2019), Qatar (Irani et al., 2018), the UAE (Abdallah et al., 2018), and other GCC countries. Traditional linear food production systems end up with huge amounts of food waste disposed of in landfill sites, leading to serious negative environmental impacts, including emissions of GHGs such as methane resulting in climate change (Manfredi and Christensen, 2009; Oldfield et al., 2016). This is in addition to the transportation cost and the increased CO_2 emitted into the air also adding to climate change. Food waste and losses take place along the whole food supply chain from harvesting, transportation, storage, processing/packaging, and distribution

Table 4
Food production in the GCC countries in 1000 tonnes, averages 2011–2018. Source: (FAOSTAT, 2019).

	Total Fruit Production	Total Vegetables	Total Eggs	Total Meat	Milk
Bahrain	19.52	324.15	2.84	24.47	14.21
Kuwait	103.03	324.15	69.56	93.42	64.82
Oman	418.32	354.10	15.51	74.25	202.75
Qatar	28.34	37.24	4.65	22.75	34.12
Saudi Arabia	2099.51	967.96	252.61	733.99	2245.01
UAE	66.19	324.15	29.01	58.64	40.25

through to consumption. In this context, circular food production is highly relevant to the region. Here, innovative, cost-effective, and environmentally friendly technologies can be used to produce high quantities of high-quality food. At the same time, the waste generated along the full supply chain is recycled as feedstock to produce high-value-added products. Along the food chain, there could be a considerable amount of food loss between retailers and consumers due to the collective factors of unacceptable quality, losses in the manufacturing process, and incomplete utilization or consumption. Food waste, being one of the main contributors to landfill, is linked to environmental pollution. GCC countries are among the top food wasters per capita worldwide (Baig et al., 2019). Composting food waste to produce biofertilizer would reduce the need for synthetic fertilizer, eliminate the environmental pollution due to landfilling of food waste, and also support the circular economy in the context of industrial ecology (Al-Rumaihi et al., 2020).

Recent studies have shown that Qatar, Saudi Arabia, and the UAE belong to the top food wasters in the world with ~600, 427 and 197 kg of food wasted per capita per year, respectively (Baig et al., 2019). Managing this huge amount of food waste has become a critical challenge for the GCC countries. There are sporadic initiatives to reduce food waste via reducing food consumption, collecting the remaining food and redistributing it to needy people, or using the food waste as animal feed (Al-Thani et al., 2017). Developing sustainable and cost-effective recycling processes for waste food is of increasing importance and considered a promising opportunity to embrace the circular economy. Food waste is generally rich in hydrocarbons, and several biological and thermochemical processes can be used to reuse, treat, convert, recycle, and extract the high-value product through biorefinery, or even to produce renewable energy. For example, biochar and biofertilizer (soil additives to improve soil quality for plant growth) can be used for soil amendment (Elkhalifa et al., 2019). This application leads to the coupling of food security with environmental security and bioenergy, which will help in reducing the operational cost of food production. Food waste can also be converted into biochar through pyrolysis. To address the feed demand of ever-growing intensive aquaculture and animal farming in the GCC countries, waste food could also be integrated into animal feed (Truong et al., 2019).

Another example is that of waste cooking oil (WCO), which is the used edible oil that cannot be reused for the same purpose. The usual practices of WCO disposal can clog drainage systems and also require an additional separating unit/chamber in the wastewater treatment plant. While the application of vegetable oils in the production could be environmentally unsustainable, the use of WCO to produce biodiesel has attracted attention (Abdul-Majeed et al., 2016). Rehan et al. (2018) reported that the obtained cost of WCO could be several times (2.5–3.5x) lower than the cost of edible vegetable oils. The feasibility studies on producing biodiesel from WCO in various cities in the GCC found it to be very attractive from both the economic and environmental sustainability perspectives (Hussain et al., 2016; Rehan et al., 2018).

In addition to the above, the GCC countries are producing 1.87 million tons of date fruits annually (Erskine et al., 2019). The waste date fruits could be used as an ingredient for fish and animal feeds. From the crushed date seeds, oil could be extracted using an appropriate solvent and could be converted into biodiesel (Azeem et al., 2016). In general, there is good potential to extract energy from waste in the region. The feasibility of extracting energy from the organic fraction of the municipal solid waste (e.g., food waste, paper, plastic, textile, hardwood, etc.) through different waste-to-energy (WtE) technologies (e.g., incineration, anaerobic digestion, gasification, and landfill gas) has been studied in the context of Bahrain (Alsabbagh, 2019).

Finally, the economic benefits of food waste utilization are tangible while technologies are available for doing this. These technologies include the following: (1) composting: degradation of polymers to organic material to be used as organic fertilizer for soil amendment (Waqas et al., 2018); (2) anaerobic digestion: degradation of the organic matter using anaerobic bacteria, to produce hydrogen and methane, which are considered as renewable energy (Abdallah et al., 2018); (3) pyrolysis: thermochemical degradation of the food waste to produce biochar, which improves the nutrient content and the water retention capacity of the soil (Elkhalifa et al., 2019); (4) hydrothermal liquefaction (HTL): production of crude oil with the possibility of extracting high-value-added products through biorefinery (although the HTL technique is not yet fully implemented in the GCC countries). Applying one of these technologies to recycle and reuse the waste will reduce the overall cost and make the process economically feasible. Table 5 presents some estimations of the economic benefits that could be attributed to waste treatment technology. The selection of a suitable process depends on the associated environmental impacts (Moult et al., 2018).

5. Discussion

5.1. Relevance, feasibility and prioritization of circular strategies

The idea of the circular economy in the food and water sectors entails several strategies and numerous applicable ideas conceptualized by this paper and mapped in the context of the GCC region. In this region, the notion of circularity in these vital sectors is highly relevant and recently receiving more attention in practice. It is especially relevant for achieving sectoral, macro-level goals of increasing local food production while improving the sustainability of water use. Self-sufficiency ratios in the region are low; e.g., as of 2012 accounting for 14.6%, 15.6%, 32.5%, 9.6%, 30.1%, and 21.2% for Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE, respectively, with an average value of 26.5% for the whole region (Alpen Capital, 2015). This is despite these ratios increasing remarkably in all countries, with Oman as the most self-sufficient country in the GCC in terms of food production in 2019, meeting 25%, 70%, and 80% of its respective dairy, fruit, and vegetable demand from local sources (Alpen Capital, 2019). For other countries such as Qatar, food self-sufficiency has become a vital goal, particularly after the blockade imposed on Qatar in June 2017 and lifted in early 2021. As a result, a holistic strategy has been developed to ensure improvement in all related sectors. One of the main targets consists of achieving 100% self-sufficiency in a number of critical commodities, including fresh poultry, and at a lower rate (70%) for

Table 5
Economic benefits of organic waste treatment in selected GCC countries.

Food waste treatment technology	Potential and advantages	Evidence of use and economic benefits in GCC countries	References
Composting	Composting enhances soil fertility and agricultural sustainability.	Saudi Arabia: total net savings of about US $70.72 million per year	(Waqas et al., 2018)
Anaerobic digestion	The anaerobic digestion strategy is more financially favorable in terms of the payback period, internal rate of return and profitability index, mainly due to the larger amount of processed waste.	Saudi Arabia: higher efficiency (25%); lowest annual capital $0.1–0.14/ton	(Ouda et al., 2016)
		Saudi Arabia: - Cumulative net savings from landfill waste diversion: 256 to 533 m. Saudi Riyal (SAR) - Carbon credits: 46 to 96 m. SAR - Fuel savings: 146 to 303 m. SAR - Electricity generation: 273 to 569 m. SAR	(Shahzad et al., 2017)
		UAE: Profitable with a net present value of 181 m. USD, compared to −127 m. USD for the anaerobic digestion strategy	(Abdallah et al., 2018)
Pyrolysis	Pyrolysis leads to the production of biochar, which can be used as biofertilizer, and syngas as renewable energy.	Qatar: Different initiatives to transform food waste to biochar and syngas via pyrolysis. 41.81% w/w (food waste input of 3984 kg/h and ~25% w/w of several food waste streams)	(Elkhalifa et al., 2019)

eggs produced locally. In this context, enhancing local food production in a way that does not exacerbate pressures on local resources, particularly water, is a common goal for all GCC states. The potential of the circular economy for achieving both water and food security in the region (e.g., through water reuse and efficiency in use) has been reinforced by several studies (Aleisa and Al-Zubari, 2017; Brown et al., 2018; Al-Saidi and Dehnavi, 2020). This is also in line with GCC-based policies, e.g., the GCC Unified Water Strategy (2016–2035) (Zubari et al., 2017).

The promotion of the above-mentioned circular strategies can play an important role in enhancing the circular economy in the Gulf region. Two observations can be synthesized from contrasting the GCC experience with our comprehensive mapping of the circular economy for the water and food sectors. First, the current efforts are far from being comprehensive. This paper has highlighted, in Table 2, a wide range of strategies and feasible options for the circular economy in the food and water sectors. Some options related to manufacturing recovery are particularly challenging. For example, utilization of the brine from the desalination process needs to be further explored (e.g., for salt production) as it has a considerable impact on the marine environment (Alberti et al., 2009). Furthermore, to enhance the circular economy, waste management and utilization strategies need to be explicit, interlinked, and comprehensive. Strengthening policies for waste management is a general requirement for the circular economy. This means enhancing municipal solid waste management policies and improving the valorization of food and organic waste. Collective waste generation in the GCC was around 120 million m^3/yr (approximately 1.21 kg/person/day), which mainly comes from the four sources of household, industrial solid, hazardous, and medical waste (Al-Maaded et al., 2012). Separation of the waste materials at source would make the use of some recycling materials economically more feasible while allowing better management of the rest of the waste. Landfills in GCC countries are linked to widespread pollution, and one means of reducing such pollution would be recycling (Hahladakis and Aljabri, 2019).

Secondly, the sequencing and prioritization of circular economic strategies require careful deliberations at national or local level. We have presented overarching strategies and feasible examples in our mapping exercise, and given concrete and technologically applicable directions in the Gulf case. In order to further advance the circular economy agenda, GCC countries need to tackle and incorporate more ambitious circular economy agendas, but also prioritize more feasible strategies for immediate actions and provide long-term investments for more demanding strategies. For example, circular strategies based on the principles of reduction and reuse can present low-hanging fruit that can be tackled in the short term and provide cross-cutting opportunities. They include improved efficiencies in extraction, manufacturing and distribution, and responsible consumption and waste management. Such strategies can be tackled at low cost through increased awareness, education, and readily available as well as economically feasible technologies of updating infrastructure and production processes. Other strategies based on the principles of recycling and recovery require more long-term efforts in testing technologies, providing economic incentives, and promoting benefits for users and producers. They include strategies such as the recovery of materials from extraction, manufacturing and distribution; waste utilization; and circular consumption. As we have outlined in this paper, the bulk of research and development activities in the Gulf center on these strategies, although the outcomes can be oriented towards the long term and based on local conditions. For example, in order to improve the recovery of materials from desalination processes, agriculture and livestock, and municipal wastewater, large investments in production redesign and serious reforms for improving the commercialization of retrieved products (e.g., pricing of water, or environmental taxation) might be necessary. Similarly, it is important to improve strategies to tackle municipal waste and to develop specific and local policies for different waste types.

5.2. The way forward for enhancing the circular economy

The three preeminent issues of circular economy presented here, namely municipal wastewater reuse, alternative water for agriculture, and food waste, can have several synergies with GCC-wide efforts to achieve better outcomes for the UN-based Agenda of the Sustainable Development Goals (2015–2030); e.g., relevant agriculture and water targets under SDGs 2 and 6, as well as SDG 12 on responsible consumption and production. The importance of the SDG agenda for the Gulf region as well as the legacies of GCC-wide environmental cooperation have been extensively analyzed by Al-Saidi (2020). Accordingly, many circular economy issues can be addressed locally through investing in the above-mentioned circular strategies and adjusting industrial outcomes. At the same time, common GCC policies can help promote the circular economy concept for the basic supply sectors. This could be, for example, through increasing awareness, developing common sustainability targets, and/or relating circular economy to achieving outcomes of the global sustainability agenda (i.e., achieving the SDGs, decarbonization, and the Paris Agreement). At the national level, the integration between the water and food water sectors in implementing reuse and circulation needs to be strengthened. The current efforts indicate increased attention to issues such as improving efficiency in extraction and manufacturing, and utilizing valuable resources such as wastewater and food waste. However, most of these resources remain under-utilized in the region. The utilization of MWW is largely confined to small pilot projects and academic research highlighting the benefits and challenges, such as inadequate strategies and economic disincentives (e.g., low water prices) (Aleisa and Al-Zubari, 2017; Brown et al., 2018). Similarly, with regard to food waste, there are no clear strategies or policies to advance this option in the region. In Saudi Arabia, for example, despite the great potential and some initiatives to reduce waste, major challenges exist regarding missing legislation, solid waste segregation, awareness, and acceptability of by-products (Mu'azu et al., 2019). In addition, many food items are subsidized, while the food culture encourages waste through lavish festivals, special events, and social gatherings (Baig et al., 2019).

These challenges are indicative of the neglect of non-technical circular economy strategies highlighted earlier, i.e., responsible consumption, circular consumption, consumption longevity, and the need to enhance current legislation, investments and policies. Legal frameworks for limiting food waste (e.g., prohibiting waste of certain items, imposing safe disposal or waste segregation, or enforcing donations of surplus food) are largely lacking in the region, although there is evidence of efforts underway to develop such laws, e.g., in Saudi Arabia (Baig et al., 2019). In fact, the bulk of relevant common laws GCC-wide are focused on hazardous waste and raising environmental awareness in general (Al-Saidi, 2020). Similarly, with regard to the utilization of municipal wastewater, there have been individual efforts and one-sided regulations, but no broader frameworks or national strategies. For example, Al-Saidi and Dehnavi (2020) reported for several GCC states (e.g., Qatar, Saudi Arabia, Oman) the existence of regulations for protection of the environment and public health in using sewage wastewater, as well as campaigns to encourage the utilization of high-quality treated wastewater. However, several studies have pointed out the need for more comprehensive national strategies with clear investment targets, as well as clear legal frameworks including standards for wastewater quality and monitoring (Aleisa and Al-Zubari, 2017; Brown et al., 2018).

Alongside legal frameworks, GCC states can adopt specific policies for encouraging the circular economy, similar to those formal policies adopted in pioneering cases such as China and Europe (e.g., the EU 2015 Action Plan for the Circular Economy, or China's 2009 Circular Economy Promotion Law) (McDowall et al., 2017). So far, there have been several individual efforts; e.g., the 2020 initiative by Saudi Arabia during the G20 meeting to create a circular carbon economy, or a 2019 coalition by the UAE government among different stakeholders to tackle the circular economy (particularly waste and recycling issues). In this context, more holistic policies might be required, while the basic supply sectors such as water and food need to be a part of such strategies due to their paramount importance for the Gulf. Future policies also need to invest in innovation and R&D in order to probe adequate technologies and understand the required market conditions. Such knowledge can help in designing the economic incentives and institutional reform required for wide-scale adoption of the circular economy.

6. Conclusions

Arid regions such as the Gulf are in serious need of interventions that improve the allocation of limited natural resources. While there are many sustainability paradigms in this regard, the circular economy concept is particularly relevant. Closing the loops through enhancing resource reuse, recycling materials, and reorganizing the value chain can advance both resource-use sustainability and economic diversification efforts in the Gulf region. So far, the bulk of worldwide circular economy interventions have been related to the manufacturing industries. In the Gulf, the basic supply sectors such as water and food are particularly important for achieving key goals of the sustainability agenda, e.g., conserving ecosystems, reducing energy use and carbon emissions, and curbing the large ecological footprints. In this regard, the mapping of circular economy applications relevant to the reality of the water and food sectors is a timely endeavor that can produce viable options for reforming these vital sectors towards a more sustainable use of resources. In this context, this paper has provided a unique circular economy framework for the basic supply sectors based on existing, broad understandings of this concept. This framework integrates and reorganizes the value chain of basic supply based on commonly used circular economy principles and multi-level perspectives of supply systems. The mapping exercise resulted in 11 circular strategies that include an extensive list of viable examples to enhance the circular economy in the water and food sectors. The paper outlined some overarching circular economy issues at the macro and meso levels, e.g., conservation, awareness, regulations, or the differentiation of food production and water reuse systems. At the micro level, there are several promising directions for better resource circularity in the food and water sectors. The paper has highlighted particularly interesting industrial applications of municipal wastewater in the Gulf; e.g., the use of organic and inorganic compounds, biomass production as feedstock, and several applications using microalgae. Treated wastewater is also increasingly recognized as an alternative resource for agricultural production. In the food sector, the conversion and recycling of food waste is resulting in viable economic opportunities for harvesting resources for renewables productions, biorefineries, or fish and animal feed. Ultimately, these applications result not only in enhanced sustainability in resource use but also in more realistic self-sufficiency policies for the Gulf region. Due to the limited scope of this paper, which has provided an overall framework and an initial mapping from a regional perspective, the local level (e.g., households, cities, municipalities) is not adequately contextualized and is left for future analyses. In addition, future research can highlight challenges for implementing particular circular economy applications within a given institutional setup, or it can provide more comparative assessments (e.g., economic feasibility, cost/benefit, or acceptance) of viable applications.

This paper has given some overarching recommendations for the success of circular economy efforts in the water and food sectors. Overall, there is a need for more comprehensive circular economy policies. In this context, non-technical circular economy strategies warrant increased attention. The current efforts in the Gulf are still missing important opportunities highlighted in the circular economy mapping; e.g., harnessing desalination-related by-products, promoting comprehensive waste management strategies, or enhancing household-level awareness of and participation in waste management. Furthermore, there is a need for prioritization of circular economy interventions by promoting low-hanging fruit based on the principles of reduction and reuse. Other more demanding interventions based on recovery and recycling require the encouragement of research and development in order to calibrate solutions to the local conditions. This process is more long-term and requires public incentives for experimentation, innovation and commercialization. Finally, legislative and policy frameworks need to encourage the concept of the circular economy in general, and its implementation in the basic food supply sector in particular. The circular economy can be explicitly pursued through broad formal policies (e.g., strategies in China or Europe), or incorporated in national policies towards achieving global commitments (e.g., the SDGs, or the Paris Agreement). Furthermore, sectoral or issue-based institutional frameworks (e.g., for wastewater utilization, waste management, or food waste) are largely lacking in the GCC region. The water and food sectors also need to be more closely linked in policymaking processes. The utilization of emerging resources such as wastewater and food waste is a cross-cutting issue, and it can be enhanced through cross-sectoral regulations (e.g., national policies on water reuse or waste utilization), infrastructural investments (e.g., infrastructure attached to wastewater plants or landfills for enhancing reuse, recovery, and recycling), and consistent efforts to promote responsible consumption (e.g., awareness campaigns, penalties for waste, or the promotion of environmental stewardship).

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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