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Perspective

Development of a Model for the Implementation of the Circular Economy in Desert Coastal Regions

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Abstract: Food production is the main challenge for developing arid regions due to the restricted access to fresh water. This study combines the environmental know-how of two coastal desert regions on the American continent with similar geographical characteristics to propose a general model for a circular economy in stressed environmental conditions. The Atacama Desert, located in Chile, is the driest place on Earth. Due to the lack of rainfall in decades, the possibility of growing food is almost impossible. The Desert of Sonora, in the northwest of Mexico, is known for its extreme aridity and temperatures over 50 °C in summer. Both deserts have continuously growing cities ranging from 400,000 to 900,000 inhabitants, where access to and management of freshwater represents an issue. A circular economy model was developed. Critical parameters for this model considered: the utilisation of solar energy for water desalination and energy production, integrated with hydroponic farming and water dosing with hydrogels for food production; microalgae for biofuels; seaweed for biochemicals; anaerobic digestion for organic waste management and nutrient recovery from wastewater sludge treatment. Regional policies and governance are needed to incentivise the adoption of circular economy models.

Keywords: circular economy; desertification; water scarcity

Citation: Cabrera-González, M.; Ramonet, F.; Harasek, M. Development of a Model for the Implementation of the Circular Economy in Desert Coastal Regions. *Land* **2022**, *11*, 1506. https://doi.org/10.3390/land11091506

Academic Editor: Luca Salvati

Received: 30 June 2022
Accepted: 5 September 2022
Published: 7 September 2022

1. Introduction

Water scarcity and desertification could affect up to 75% of the world's population by 2050. Due to climate change, the world needs to prepare for desertification and water scarcity, and the regions subject to drought and extreme weather conditions must lead the way.

A circular economy model focusing on maximising the efficient utilisation of water resources is needed to ensure the Sustainable Development Goals (SDGs) of good health and well-being (SDG 3), clean water and sanitation (SDG 6), zero hunger (SDG 2), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), and climate action (SDG 13).

The restricted access to fresh water in desert regions represents a challenge in their food production. Integrating their food production systems with state-of-the-art nutrient recovery systems like anaerobic digestion can close the water and nutrient loops. Desert Coastal Regions (DCRs) have a unique environment with abundant seawater and solar radiation resources.

Water desalination is the main source of fresh water in DCRs. Minimising water desalinisation costs is one of the significant challenges for developing a circular economy in these regions. In addition, maximising freshwater usage for agricultural, commercial, industrial and residential use also represents a challenge.

The transition from a linear to a circular economy requires technology, sustainable processes, innovation, products and services [1] that all have to be developed wisely between stakeholders (private sector, government, and citizens), integrating public policies and laws. On this transition, water-management utilities are crucial to push the water sector into a more sustainable development [2].

However, a circular economy model cannot be universal; it depends on the climate conditions, biodiversity, and geographical location, and the implementation will be laid on government policies.

2. Environmental Characteristics of the Atacama Desert, Chile, and Sonoran Desert, Mexico

The Atacama Desert (AD) is the driest non-polar and oldest (since the Jurassic period to Miocene, 5,000,000 years ago) desert on Earth [3]. The AD is located on the western coast of central South America, beside the Pacific Ocean, from the north of Peru (5° S), ending close to La Serena, Chile (30° S) [4]. The AD's main characteristics are toxic elements, strong oxidising conditions, extreme aridity, high ultraviolet radiation levels, and low-to-zero concentration of soil carbon [3]. Additionally, precipitation in the AD is scarce (20 to 80 mm per year) and is intensely concentrated in the summer [5], with January and February being the two "rainiest" months. Due to this low level of rainfall, there is almost a complete absence of vegetation [6].

The average annual temperature is 16.1 °C, with a maximum temperature of 36 °C and minimum of −3.79 °C [4]. The hyper-arid climate is controlled by the upwelling cold Humboldt current in the Southeast Pacific Ocean and the high-pressure belt generated by the global Hadley circulation [7]. In addition, the AD, specifically the Antofagasta region, hosts Chile's major extractive mining economy. Antofagasta represents 51% of the mining Gross Domestic Product (GDP), and 26% of the world production of lithium comes entirely from the Atacama Salt Lake [8].

On the other hand, the Sonoran Desert (SD) is located between 23° N and 33° N in North America including the states of Sinaloa and Sonora, and the Peninsula of Baja California [9]. The SD covers an area of 260,000 km^2 [10]. This region is surrounded by the Gulf of California and the Pacific Ocean and has less than 50 mm of rainfall per annum; however, Sonora's plain can receive up to 250 mm [10]. The temperature within the SD drops to −5 °C in winter, while in summer it can be up to 50 °C. The SD is one of the hottest deserts on Earth [11].

3. Circular Economy Model

The Circular Economy (CE) is a paradigm changer of the current linear production systems. In order to achieve major breakthroughs, leveraging slight shifts in perspectives is needed [12].

The CE concept was first introduced by Pearce and Turner [13] explaining the interdependence between the environment and the economy in their book. Among the different CE definitions, the following two exemplify its context.

The CE can be defined as "an economic system that replaces the 'end-of-life' concept with reducing, reusing, recycling, and recovering materials in production, distribution, and consumption processes" [14].

The Ellen Macarthur Foundation [15] defines the CE as "a new economic model that is restorative or regenerative by design and focuses on resource-related challenges for economies and businesses". In the CE, the life cycle must be well planned to eliminate waste by utilising it as a feedstock or recirculating it.

CE can be successfully implemented as a management model to achieve sustainable development. This management model can be used for establishing and executing regulations to protect the environment; establishing a system of preferences for circularly managing resources; promoting cooperation between stakeholders to achieve a collaborative sharing economy; and strengthening the social capital [16]. Studies from Neves and Marques [17] have shown the drivers and barriers to transition from a linear to a circular economy, evaluating the role of social, environmental, and economic factors. The authors recommend that, in order to achieve an effective transition to a CE, promoting policies targeting specifically older and less-educated people is needed, due to the lack of environmental awareness of these groups. Smol, Adam, and Preisner [18] proposed a circular economy model for the water and wastewater sector focusing on the circular economy principles of reduction, reclamation, reuse, recycling, recovery, and rethink. They found that the sustainable management of water resources is not sufficient to achieve the CE objectives and that a special emphasis is needed on wastewater disposal.

Furthermore, Mannina et al. [2] reviewed the water and sewage sludge policies in Europe and analysed the barriers, bottlenecks, opportunities and challenges of applying the CE in the wastewater sector. The authors concluded that the barriers should be considered as challenges to guide policymakers and water-management utilities to resource recovery decisions.

According to Ferronato et al. [19], circular economy models vary in every context due to social, environmental, financial, and political differences; hence, they cannot be equivalent for every context. The authors emphasize that the implementation of a CE model should consider applying specific plans depending on the needs of the country, state, city or community.

On the other hand, Ahmed, Mahmud, and Acet [20] exposed that circular economy models are usually applied in developed countries but rarely in developing ones. In their scientific research, they mentioned that the major practices for a CE in North America (United States) are making homes using old containers, making carpets out of plastic, recycling and reusing used clothes and making jeans from waste plastic bottles; while in South America (Chile), the focus is on recycling and reutilisation of wastewater, and recycling of solid wastes.

Research on desert areas for a circular economy is rare. For this reason, this study focused on a macroscale model for DCRs.

This study proposes a circular economy model integrating state-of-the-art technologies with the two most abundant natural resources in DCRs: solar radiation and seawater. Solar energy can be harvested from solar panels to provide electricity to a desalination plant.

A circular economy in DCRs can be possible if all the natural resources are used sensibly. One such resource is the availability of seawater next to the desert, which poses an advantage in fighting water scarcity with a desalination process to supply the water requirements fully or partially for inhabitants, food production, and industrial processes.

Another advantage of desert areas is the high solar radiation, which can be used to produce energy through solar panels.

Furthermore, clean energy production is possible in deserts, and it will fulfil the requirements for water desalination. An additional advantage is the availability of non-arable land that can be utilised for microalgae cultivation in open raceway ponds or photobioreactors. An alternative for non-arable land farming for fresh food production is hydroponic systems. Moreover, seaweed cultivation for food production is also possible.

An example of technology integration was set by Bermudez-Contreras et al. [21], who designed a reverse osmosis desalination plant powered with photovoltaics for the State of Baja California Sur. To produce 1 m^3 of potable water, including pre-treatment and post-treatment processes, 3.5–4.5 kWh are needed [22]. The energy demand of the desalination plant can be satisfactorily filled with solar energy (see Section 3.2).

The desalination process has the disadvantage of producing a sidestream: brine. Brine's main constituents are the salts removed by reverse osmosis, which are discarded in the seawater. Therefore, brine is a potential contaminant and is a candidate for environmental damage that must be mitigated since sustainability is key in a CE process. However, brine can be converted or recovered into new products (ions or molecules) like MgO, Rubidium, Uranium, NaOH, Cl_2, H_2, acids, bases, Lithium, and salts in pure form [23] to avoid environmental impact. High solar radiation in arid regions can be an excellent ally for evaporating the brine in a closed and controlled environment. The evaporation process can be helpful for mineral and nutrient recovery like phosphate, which could be applied in hydroponics as a fertiliser (see Section 3.3).

For the model proposed, once the water has been desalinated, the freshwater is utilised for hydroponic farming in the case of non-arable soil (e.g. Antofagasta) or it can be used for irrigation water dosing with hydrogels in the case of semi-arable soil (agricultural land in Sonora). Seawater can be utilised for microalgae production in raceway pounds, and seaweed can be farmed in the ocean. Seaweed is utilised for biochemical production, while microalgae are used for biofuels production, among other applications.

Then, the residue streams from the agricultural systems, microalgae and seaweed can be processed through anaerobic digestion for biogas production. Nutrients can be recovered from the digestate, while biogas is upgraded into biomethane, utilising CO_2 as feed for the microalgae. A combined heat and power unit can also be employed to produce electrical energy for the grid and heat for the desalination process, capturing the exhaust gas, purifying it, and feeding the CO_2 to the microalgae. The digestate can be directly applied in agriculture, or the recovered nutrients can be added to the hydroponic system. Byproducts, such as glycerol from biofuel production, improve biogas yields in anaerobic digestion.

The details discussed above can be visualized in Figure 1, which details a schematic of a circular economy model that could be implemented in coastal arid regions.

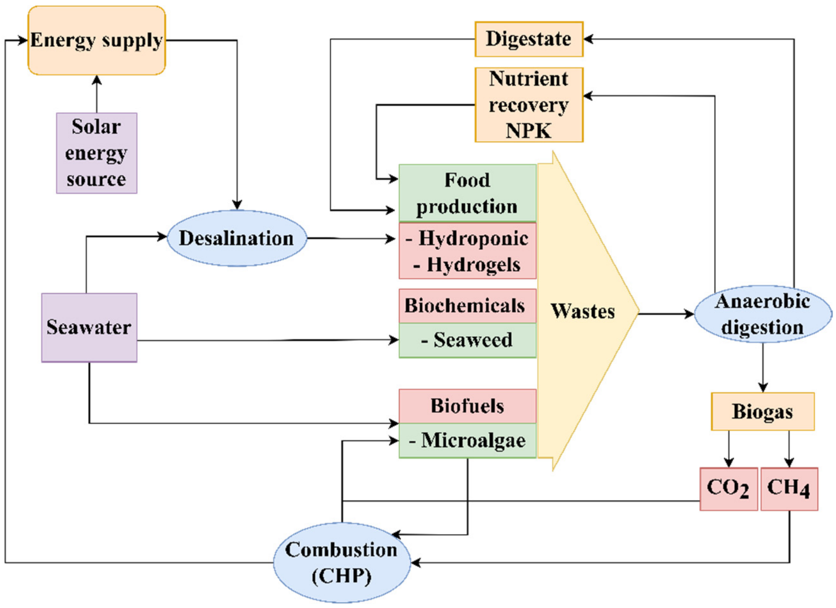

Figure 1. Schematic of a suggested circular economy to develop in coastal arid regions.

This model represents a macro scale system of a CE and does not consider other factors like industries, pollution, tax policies, environmental laws, etc. Nevertheless, this model can be considered as a starting point for implementing an action plan for the social economy in Chile, Mexico or Latin America, as the European Commission suggested [24].

The fundamental principle of the proposed model is integrating state-of-the-art technology with abundant natural resources, i.e., ocean water and solar radiation, exploited through renewable energy and responsible reintegration of treated brine into ocean waters. In summary, this paper proposes the use of desalinated water for food production using a hydroponic or irrigation system that doses water with hydrogels. Whereas, seawater will be utilised for macroalgae and microalgae farming to produce biochemical and biofuels. Crop and algae residues will be processed through anaerobic digestion to obtain biogas and digestate, where the biogas will be upgraded, and the carbon dioxide stream is fed to the microalgae. Nutrients will be recovered from the digestate and used for food production. Alternatively, the biogas can be burnt in a combined heat and power unit to produce electrical and thermal energy, from which the resultant CO_2 can be fed to the microalgae.

In the following section, the subsystems of the model and their current state in the Atacama and Sonoran deserts are described.

3.1. Water Desalination

Water scarcity in desert places is a challenge for the inhabitants of the regions. The World Resources Institute has ranked Chile as number one and Mexico seventh in having a high baseline water stress [25]. Nevertheless, AD and SD have the advantage that they are next to the Pacific Ocean; therefore, water desalination plants play an essential role in freshwater conversion. Water desalination (WD) can be achieved by reverse osmosis with membranes or thermal energy. In reverse osmosis desalination, membranes remove all the salts and unwanted particles to convert seawater into drinking water (Figure 2). However, WD is a costly, energy-intensive and non-environmentally friendly process. In South America, Chile has the most extensive system of desalination plants [26]. The oldest desalination plant started operations in 2003 in Antofagasta (Figure 3A). The plant supplies 85% of the Antofagasta population with potable water, making it the biggest desalination plant in Latin America. In total, in Antofagasta, it is produced 73,440 m^3 of desalinated water per day [27].

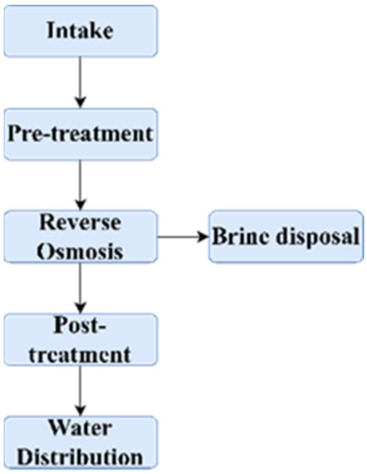

Figure 2. Flow diagram of water desalination.

Chile discards the brine by pumping it back into the ocean; however, other countries utilise other disposal methods, such as evaporation ponds, deep-well injection, conventional crystallisers and discharge to the sewage system [28].

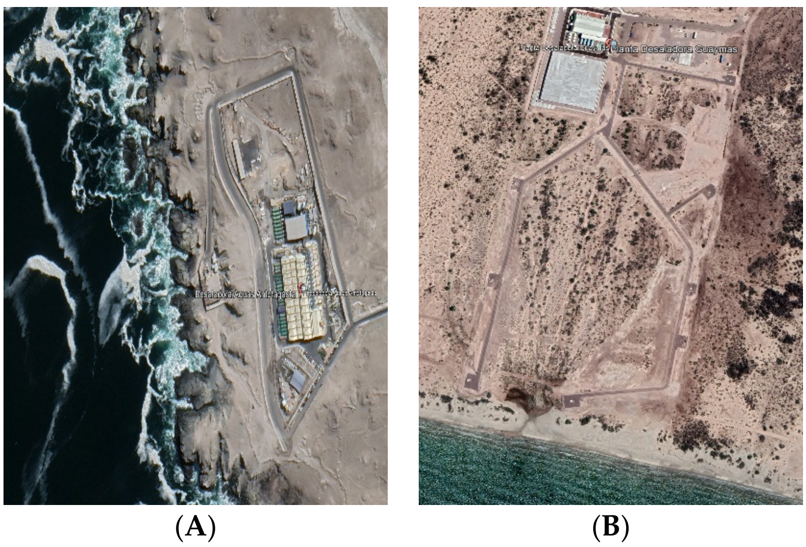

Figure 3. (**A**) Desalination plant in Antofagasta, Chile [29]. (**B**) Desalination plant in Guaymas, Sonora, Mexico [30].

Mexico has over 435 desalination plants, of which 71 are in the state of Baja California Sur [31], part of the Sonoran Desert. In the case of Sonora State, in 2008, three desalination plants were approved with varying capacities of 200 L s^{-1} for Guaymas (Figure 3B) and Hermosillo, and 120 L s^{-1} for Puerto Peñasco [32]. Robles-Lizárraga et al. [33] designed an optimal desalination plant for the city of Puerto Peñasco in Sonora. The 200 L s^{-1} (720 m^3 h^{-1}) desalination plant in Guaymas started operations this year to provide fresh water to its city [34].

The ambitious binational water desalination opportunities report for the Sea of Cortez aims to find the most optimal sites to install desalination plants to provide fresh water to the states of Sonora and Baja California Norte in Mexico and Arizona, Nevada and a small part of California in the United States of America [35].

3.2. Solar Energy

Globally, the Atacama Desert in Chile is one of the best places for astronomy due to its lack of clouds and possesses one of the most significant solar resources. Additionally, global irradiation in the AD is above 2500 kWh m^{-2} $year^{-1}$, making it the place with the highest radiation level on the planet [36]. This solar potential means that the production of energy through solar panels is possible. Currently, nine of the ten biggest solar plants in Chile are in the AD (El Romero, Solar Bolero (Figure 4), Luz del Norte, Finis Terrae, Cornejo Solar, Amanecer CAP, El Pelícano, Carrera Pinto, and Pampa Solar Norte). Antofagasta has one of South America's biggest solar power plants, producing 439.1 GWh [37].

Figure 4. Bolero Photovoltaic Park, Sierra Gorda, Antofagasta, Chile [38].

In the state of Sonora, the eighth biggest solar plant in the world, comprised of 240 hectares, is currently under construction, which will harvest 1000 MWh [39]. If just 1% of Sonora's land was used for solar projects, it could provide enough energy to power all of Mexico [40].

3.3. Hydroponic Systems for Food Production

Hydroponic systems are soilless agricultural systems that grow plants in water with mineral nutrients. Hydroponics have many advantages compared to traditional agriculture due to limited water consumption, a limited need for pesticides, and a lack of arable use. Additionally, the system is completely controlled in terms of nutrient supply, temperature, light, humidity, and carbon dioxide concentration [41]. In desert regions, it is advantageous to apply these techniques since there is a lack of fertile soils for agriculture combined with a limited freshwater supply.

In Antofagasta, Chile, specifically in the “La Chimba” and “Altos la Portada” zones, hydroponic cultures have been developed to supply a fraction of the food requirement for the population. The main products available through this type of agriculture are lettuces, spinach, coriander, parsley, bell pepper (Figure 5), chard, basil and others. These vegetables are sold in the city farmer’s market “La Vega Central”, as well as in supermarkets, and on the internet. The hydroponic system is supplied by desalinated water, making it the most extensive hydroponic production in Chile.

Figure 5. Hydroponic system of bell peppers, Alto la Portada, Antofagasta, Chile.

Before the hydroponic system was set up in Antofagasta (2012), all the fresh vegetables came from Arica or La Serena (the vegetables produced at present by hydroponics). Terrestrial transport was needed due to the long distances to fertile soils (La Serena to Antofagasta: 865 km; or Arica to Antofagasta: 716 km) to provide fresh food to consumers.

In the case of Mexico, Rafael Martinez-Cordova et al. [42] evaluated an integrated multitrophic aquaculture system that utilised fish aquaculture of *Tilapia* spp. and the agriculture of jalapeño and mini bell peppers in greenhouses in Hermosillo. However, they found that jalapeño pepper plants were not an adequate candidate for hydroponics in the proposed system. De Anda and Shear [43] stated that vertical hydroponic agriculture could help resolve the food shortage caused by non-arable land and water scarcity. Shrivastava et al. [44] proposed a vertical automated hydroponic system that monitors the water flow, temperature, moisture and nutrients present in the water, while also recycling the utilised water. The authors developed a vertical hydroponic system that can reduce water consumption by up to 70%.

In Mexico in 2010, 60% of the installed hydroponic greenhouses failed due to the absence of qualified technicians, lack of producer training, and inadequate location of markets [45]. However, by 2014, more than 20,000 ha were working with hydroponics [46].

3.4. Water Dosing with Hydrogels for Agriculture

According to the World Economic Forum [47], agricultural production systems need to increase their productivity by two-thirds to meet the projected demand in 2030 caused by the population increase. The implementation of more water-efficient systems is needed to meet this demand.

Hydrogels are yield enhancers and soil conditioners, which can retain nutrients and water, and then release them over an extended period [48]. Kalhapure et al. [49] found that applying hydrogels increases productivity in terms of crop yield.

The emergence of hydrophilic polymers based on polyacrylamide occurred in the 1950s in the United States of America. Over the years, its hydration capacity has improved from 20 to 400 times its weight [50].

Hydrophilic polymers help improve the water absorption capacity, allowing to improve the efficiency of water use, the effect of which depends on the quality of the water, with the hydration capacity of the polymer being significantly reduced in the presence of salts in the irrigation water [51].

The combination of superabsorbent hydrogels and fertiliser produces slow-release fertiliser hydrogels, improves plant nutrition, and reduces the environmental impact of conventional fertilisers since there are fewer losses by evaporation and the irrigation frequency is reduced [52].

López-Elías et al. [51] implemented hydrogels for the greenhouse production of Anaheim peppers. They found that this initiative favours the reduction of the volume of water applied and the frequency of irrigation, favouring the increase in chlorophyll content without affecting the crop.

Macías-Duarte et al. [53] performed a study on the integration of hydrogels with irrigation systems for the cultivation of olives. They found that, with an irrigation deficit of 50%, the yields and quality of olive trees were not affected, nor was the soil's moisture content.

3.5. Microalgae Culture as a Biomass and Seaweed Farming and Processing for Food Supply and Biochemicals

Microalgal biomass represents an attractive feedstock for producing human protein supplements, liquid fuel, feed for the aquaculture industry, biofuels and CO_2 capture. In addition, microalgae produce high-value byproducts like pigments, enzymes, lipids, sugars, sterols and vitamins [54]. The advantages of microalgal biomass production are that they can be grown using wastewater, seawater, brackish water, and sunlight, and there is no need for arable lands [55]. Consequently, AD and SD have the potential for microalgae production due to the proximity to the ocean, sunlight, and the availability of non-arable soils, making an ideal scenario for biomass production. Rasheed et al. [56] described the possibilities of cultivating microalgae in Qatar, which is located next to the Persian Gulf. The climate conditions of Qatar improved the microalgae's nutritional potential in terms of lipids, polyunsaturated fatty acids, and proteins.

Furthermore, Schipper et al. [57] have demonstrated four novel isolated microalgae strains from the Arabian Gulf. Their results suggested that *Picochlorum* sp. can grow in elevated temperatures (40 °C) and high carbon dioxide concentrations, making them promising organisms for CO_2 sequestration. Regarding biofuels, Gao et al. [58] successfully improved *Chlorella* sp. cultures using a mixture of seawater and domestic sewage for biofuel production, obtaining the highest productivity of lipid when 60% seawater was used. On the other hand, more than 70 different local microalgae species have been characterised and isolated in Mexico. However, only a small fraction of them has been explored for producing valuable products [59]. In Chile, some attempts to investigate phycoremediation using *Muriellopsis* sp. in the AD at a pilot-scale level have been done [60].

In the scientific literature, many applications and benefits of microalgae have been described; hence, microalgae production could be implemented in the CE model for DCRs due to their intrinsic value and low water demand.

Regarding macroalgae production, high-interest compounds have been identified for potential applications. Namely, fatty acids, phenols, pigments, polysaccharides and monosaccharides are target compounds obtained from seaweed [61].

The seaweed industry is most developed in Asian countries where most of the seaweed is cultivated with smaller amounts harvested or obtained from the wild. While in Europe, most of the seaweed industry utilises imported algae or is obtained from wild harvesting [62]. In the case of Latin America, Chile contributes 88% of the total seaweed harvested, while Mexico only contributes 3.7% [63].

According to the project AlgaHealth [64], ocean farming in the desert is needed to supply all the required dietary supplements. However, a lack of research on this topic has been found.

3.6. Biogas Production

The popularity of biogas production for energy production and waste neutralisation has been increasing worldwide since the early 2000s. Biogas is composed of the following concentrations: 60–70% methane, 30–40% carbon dioxide, 1–2% nitrogen, 1000–3000 ppm hydrogen-sulfide and 10–30 ppm ammonia [65]. Biogas is obtained by a process called anaerobic digestion.

Anaerobic digestion or degradation is a biological process that converts organic carbon by subsequent reductions and oxidations to its most reduced state (CH_4) and its most oxidised state (CO_2) in the absence of oxygen [65]. Biogas main applications are in the area of treatment of sludge from wastewater, Organic Fraction of Municipal Solid Waste (OFMSW), manures, agricultural and industrial residues [66].

In the case of Mexico, the federal government has expressed its interest to develop Wastewater Treatment Plants (WWTP) integrated with anaerobic digestion to produce and use their own energy to decrease operational costs [67]. An example of this is the WWTP of Hermosillo, which has two 12,000 m^3 anaerobic digesters, three combined heat and power units of 874 kW (two in operation and one on stand-by) and two gas holders of 2150 m^3 [68].

Kim, Lee, and An [69] proposed retrofitting the biogas plant of Hermosillo's main WWTP for co-digestion with the OFMSW, to generate electricity and heat for the WWTP. Whereas, Noyola et al. [70] carried out three pre-feasibility studies for anaerobic digestion in pig farms in Sonora; an up flow anaerobic sludge blanket at NORSON slaughterhouse and co-digestion of industrial residues at the WWTP of Hermosillo.

Mexico has no legislative framework allowing the utilisation of digestate from pig slurry for agricultural purposes [70]. Currently, there are no anaerobic digestion plants operating with manure or OFMSW on the AD or on the SD.

3.7. Nutrient Recovery from Wastewater Treatment Streams and Anaerobic Digestion

The increase in agricultural practices has led to the generation of a large amount of nutrient-rich wastewater [71]. Even though several reports address nutrient recovery technologies and the challenges of nutrient recovery from different nutrient-rich wastewaters, there is no standardised methodology to assess the feasibility of real-life applications [71].

Domestic wastewater treatment is a mature technology that impacts human health and the environment [72]. The two main alternative domestic wastewater treatment processes that recover energy and nutrients are low energy mainline for phosphorus recovery and partition–release–recover for nitrogen and potassium recovery [72].

Nutrient recovery technologies can be divided into low energy and high energy consumption. Struvite formation and ammonia stripping are two easily operated technologies that, when compared to membrane technologies, can be implemented at a low energy cost [73]. Membrane distillation, electrodialysis, reverse osmosis, and nanofiltration are effective nutrient recovery technologies, but their long-term operation is limited by membrane fouling [73].

A particular case of nutrient recovery is planned for the WWTP in Marineo (Italy), where phosphorus and nitrogen will be recovered from the effluent streams by means of two adsorption columns [2]. In the state of Sonora, there are examples of utilising natural resources efficiently, such as the solar-powered wastewater treatment plant (Figure 6) serving the city of Nogales with a 220 litres of sewage per second installed capacity [74].

Figure 6. Solar-powered wastewater treatment plant in Nogales, Mexico [75].

Since the 1990s, the General Law of Ecologic Equilibrium and Protection of the Environment has pushed for wastewater treatment in Mexico. Article 92 of this law (when translated) states that "to ensure the availability of water and lower the levels of waste, the competent authorities will promote the saving and efficient use of water, the treatment of wastewater and its reuse" [76].

Due to water scarcity in Hermosillo, companies, schools, residential complexes, hotels and the airport have private wastewater treatment plants summing to 44 [77]. The two main government-owned WWTP in Hermosillo have a capacity of 2500 L s^{-1} (Figure 7) and 113 L s^{-1}, respectively.

Figure 7. The wastewater treatment plant in Hermosillo, Sonora, Mexico [78].

Water scarcity in DCRs can be decreased by implementing mature, proven technologies as the ones described above. Figure 8 shows the process followed in this perspectives article.

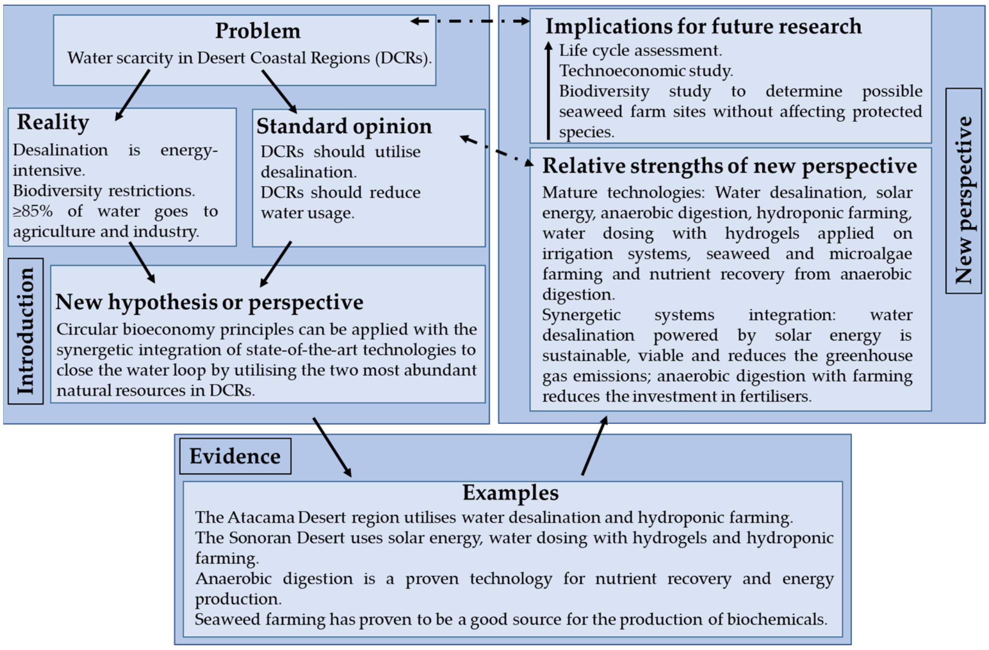

Figure 8. Scheme of the process followed in the article.

4. System's Feasibility and Evaluation

According to Corvellec, Stowell, and Johansson [79], a circular economy model needs to be accountable for its achievements and shortcomings; hence, the feasibility of implementing the proposed technologies needs to be addressed regarding the environmental risks, ecological sustainability, the economic viability and the technology readiness level.

To evaluate the proposed circular economy model, attributes were evaluated for the processes and products. The products and processes were evaluated from 0 to 10, with zero being poor performance and ten being outstanding performance. The four evaluated attributes are technology readiness level, economic viability, ecological sustainability, and environmental risks. The technology readiness level assesses if the technology is ready for deployment; ecological sustainability evaluates the environmental effects; environmental risks refer to the irreversible environmental damage that could be done if the products or processes are not managed correctly; and economic viability evaluates the capital costs. Figure 9 shows the results of the evaluated attributes of the proposed circular economy model.

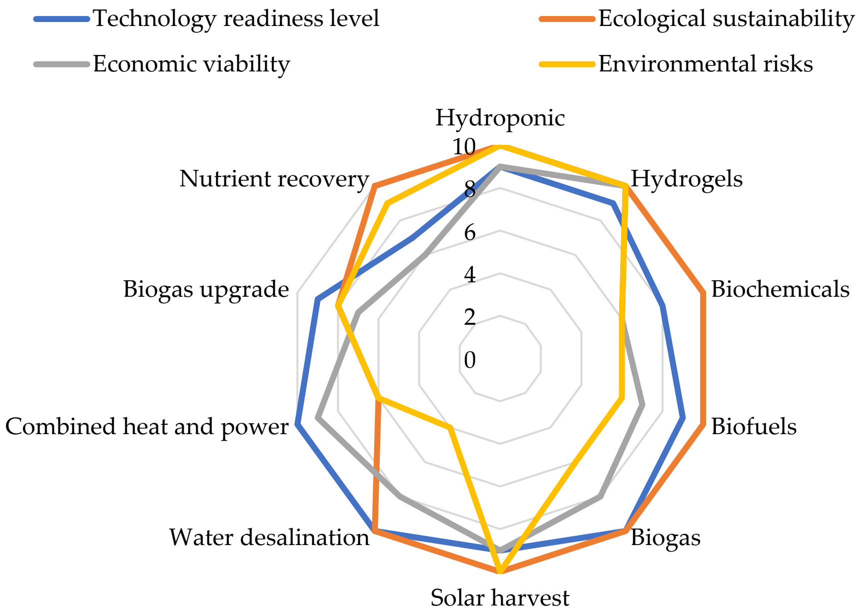

Figure 9. Attributes evaluation of processes and products of proposed circular economy model.

Out of the evaluated processes in Figure 9, the environmental risks are present in most of them except on solar energy harvesting, hydroponic system and water dosing with hydrogels. The worst performance for the ecological sustainability attribute is combined heat and power cogeneration, since there is an energy loss from 24% to 45% in the power generation [80]. Most of the processes analysed are mature, hence the technology readiness level is high. There is economic viability in most cases, being the lowest performance nutrient recovery.

A detailed evaluation is needed before deploying the proposed circular economy model for DCRs. To successfully integrate these technologies, feasibility can be assessed by a life cycle assessment, a techno-economic analysis, and a biodiversity study.

Finally, regional policies and governance must be available to incentivize the adoption of CE models.

The closest policy initiatives related to a CE in Chile are found in law No. 20,920 [81], residues management and recycling campaigns. However, it does not mention a circular economy per se. Nevertheless, the new Chilean constitution proposal mentioned that the state would promote the circular economy but did not explain how [82]. The priority products for recycling mentioned in article 10 of the Chilean law are lubricant oils, batteries, electric and electronic devices, containers and packaging, and tires.

The Ministry of Environment of Chile, as well as the Ministry of Economy, Development and Tourism of Chile, the Chilean Economic Development Agency (CORFO) and the Sustainability and Climate Change Agency, have made efforts to implement a Chilean circular economy by 2040 [83]. Seven goals are set to carry out a circular economy in Chile by 2040, in the following order according to priority (Ministerio de Medio Ambiente 2020): to increase green employment, decrease the municipal solid waste by inhabitants and the total waste generation by GDP, to increase the resource productivity, the general recycling rate and the recycling of municipal solid waste, and to recover sites affected by illegal waste disposal (Figure 10).

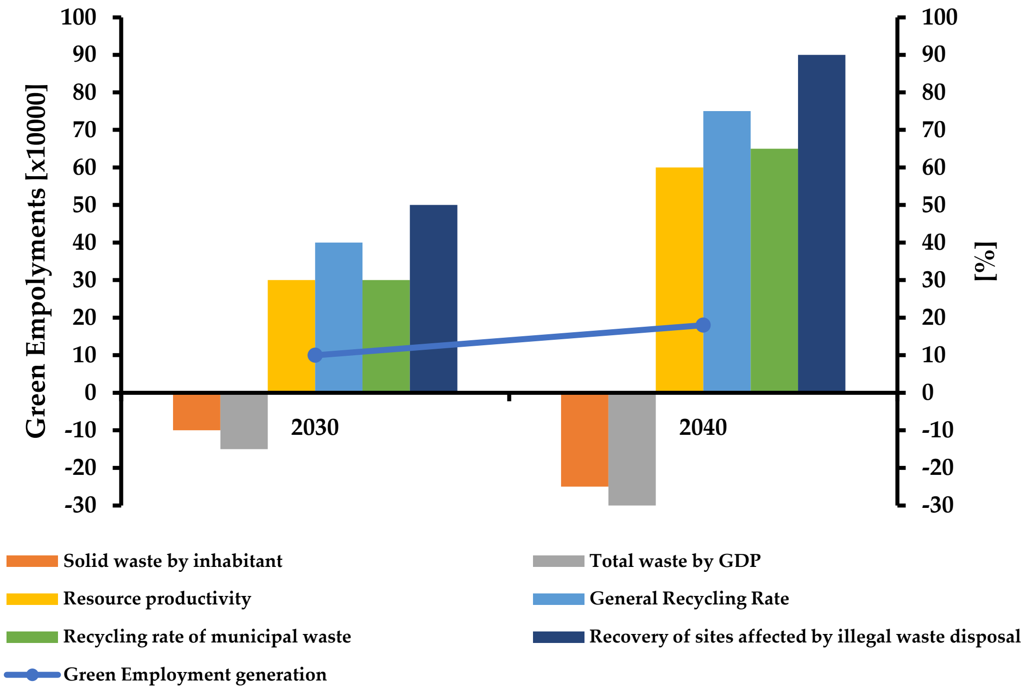

Figure 10. Long-term goals in Chile to implement a circular economy, adapted from [83].

In the case of Mexico, in November 2021, the General Law of Circular Economy was approved [84]. The law aims to establish the principles of the circular economy through legislation on waste and contribute to the fight against climate change and protecting the marine environment. Valenzuela-Corral and Hinojosa-Rodriguez [85] studied the implementation of the circular economy in the south of Sonora, considering the ecological, political, social, and technological factors. The authors concluded that, to implement the circular economy in this region, companies and governments must collaborate, innovate and have a vision of change. Cansino-Loeza et al. [86] proposed a framework for developing a model that provides the optimal allocation, quantifies, and maximises the security of the water, energy, and food sectors in the state of Sonora.

International organisations, governments, investors, and businesses must work together for this model implementation. International organisations can put the circular economy on the global climate agenda, governments can enable policies and put the necessary infrastructure in place, investors are needed to mobilise capital towards circular economy solutions, and businesses can make intelligent decisions on how to design and sell their products and services [87].

5. Conclusions

A circular economy model for the development of coastal desert regions has been proposed complementing the conditions and experiences of the Atacama Desert and the Sonoran Desert.

As reviewed in this paper, integrating desalination and hydroponic farming, solar energy and wastewater treatment, wastewater treatment and biogas production, and hydrogels and irrigation are already a reality in the Atacama Desert and the Sonoran Desert. Macroalgae offshore farming, microalgae production and nutrient recovery are the missing components needed for the implementation of the proposed model.

Studies are needed to ensure environmental, social, and economic sustainability before deploying pilot testing. Within these studies, life cycle assessment, techno-economic analysis, and a biodiversity study are recommended to ensure the deployment of this model without harming the environment or protected species.

Author Contributions: Conceptualization, F.R. and M.C.-G.; methodology, F.R. and M.C.-G.; validation, F.R. and M.C.-G.; formal analysis, F.R. and M.C.-G.; investigation, F.R. and M.C.-G.; resources, M.H.; writing—original draft preparation, F.R. and M.C.-G.; writing—review and editing, F.R. and M.C.-G.; visualisation, F.R. and M.C.-G.; supervision, M.H.; project administration, M.H.; funding acquisition, M.H. All authors have read and agreed to the published version of the manuscript.

Funding: This project has received funding from the European Union's Horizon 2020 research and innovation programme AgRefine under the Marie Skłodowska-Curie grant agreement No 860477.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to express their great appreciation to the AgRefine colleagues Priya Pollard, Charlene Vance, and Mariana Cerca for proofreading the manuscript for English language correctness.

Conflicts of Interest: The authors declare no conflict of interest.

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