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Evaluation of the Circular Economy in a Pitahaya Agri-Food Chain

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Abstract: Over the last decade, the circular economy (CE) has attracted attention due to the current unsustainable model of production and consumption, which involves an increased resource use and depletion. Agri-food is one of the key sectors where action must be taken to ensure the transition to a more sustainable development model in line with circular economy principles. This study aims to evaluate the potential of implementing the circular economy in the pitahaya agri-food chain in Ecuador. The research was conducted from 2019 to 2021, during which a checklist was applied that included 91 items grouped into nine dimensions: source or supply of materials, design, manufacturing, economic circle, distribution and sales, consumption/use, 4R, remanufacturing, and sustainability. The level of the circular economy evaluated in the study was low (2.14 points out of 5). Therefore, improvements are required in the agri-food management of fruit cultivation and processing. Critical points were identified and strategies were proposed to increase competitiveness, improve environmental performance, and promote the implementation of the circular economy in this production chain. A final recommendation is to explore research on the concept of CE in the sector, mainly focused on the valorization of biomass as a contribution to the bioeconomy in order to contribute to the country's growth within the context of sustainability.

Keywords: agri-food chain; pitahaya; circular economy; sustainability

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1. Introduction

During the last decade, the circular economy (CE) has received increasing consideration worldwide in terms of its potential to overcome the current production and consumption model, which is characterized by an increased resource use and depletion [1]. CE is defined as "a model of production and consumption that involves sharing, renting, reusing, repairing, renewing, and recycling existing materials and products for as long as possible and minimizing waste" [2]. This offers a better alternative to the current model of economic development—the "take, make, and dispose of" model [3]. The objective of CE is economic, environmental, and social sustainability [4,5].

A circular economy is proposed to boost economic and environmental development while preserving and enhancing natural resources and renewable flows [6–8]. In that sense, it can tackle the current problems of modern society, such as biodiversity loss, climate change, resource depletion, water scarcity, population growth, and economic problems [1]. The advantages of CE-based systems are well known, from reducing environmental impact by minimizing waste to redesigning products/materials with increased economic benefits [9,10]. Therefore, CE aims to reshape production systems globally to follow the ideal goal of a waste-free economy [11].

On the other hand, CE, such as all other sustainable models, requires not only innovative concepts, but also innovative actors; often, its implementation must be supported by stakeholders to enable changes in policies and decision-making tools [12,13]. In this sense, the adoption of strategies by companies to improve the circularity of the production system also requires collaboration with other companies along the supply chain to achieve the most efficient circular model possible [14,15]. Implementing a CE is not always an easy undertaking, as it often encounters biophysical limits, including high energy requirements for resource recovery and the loss of resource quality [16].

Agricultural activities represent the largest proportion of human land use and cause a variety of impacts on the environment [17]. As agricultural activity has intensified over the years, the use of synthetic pesticides, fertilizers, and other (sometimes toxic) inputs has also increased, causing major impacts such as soil degradation [18,19] and water contamination by nitrates, phosphates, and pesticides [20]. These also emit greenhouse gases, methane, and nitrous oxide, contributing greatly to other types of pollution affecting both air and water, even causing a great threat to human health [21]. As a result, the use of sustainable production methods is sufficient to combat the negative effects of agriculture on various ecosystems [22,23].

Pitahaya fruit *(Selenicereus megalanthus*, K. Schum. Ex Vaupel, Moran) is a perennial crop that has become an agricultural fruit product of high commercial value in Ecuador [24]. The nation has become a major producer of pitahaya, alongside Colombia and Israel [25]. These countries even export this product to Canada, Holland, Hong Kong, Singapore, Spain, and the United States [26]. Its cultivation, in recent years, has become one of the main economic sources of the Ecuadorian province of Morona-Santiago, specifically in Palora Canton, where there are extensive pitahaya plantations. According to statistics (2018) from the Ministry of Agriculture and Livestock, 2000 established hectares of pitahaya [27] are in the area.

The commercial production of this fruit requires an extensive application of controllers, chemical fertilizers, and pesticides. These generate greenhouse gas (GHG) emissions, mainly carbon dioxide (CO_2) [28], methane (CH_4), and nitrous oxide (N_2O), that contribute to global warming [29]. Moreover, the continuous growth of this agricultural production is causing an excessive increase in crop waste and processing [30]. As a result, measures in the circular economy and biomass valorization can help reduce the amount of waste and pollution generated by human activity. When the products, materials, and resources resulting from productive processes are valorized, they close biological cycles. CE addresses environmental priorities while also allowing for the resolution of some current issues, such as resource depletion [31].

Several literature reviews have addressed the development of innovative CE models in the agri-food sector [1,32]. Among the challenges of agri-food chains are the problems of resource scarcity, food loss, and waste generation along the supply chain. CE has emerged and can be conceptualized under different material and energy cycle flows deployed at three circular levels (business, regional, and societal) [33], despite the difficulty of defining a single circular economy model in the agri-food sector. In that sense, integrating different stages of the supply chain with circular economy models and tools is necessary in order to create a closed-loop agri-food system [32]. One of the main difficulties of global supply chains is food waste and losses. Ref. [34] proposed a conceptual model for its prevention using a systems approach through the CE concept. Furthermore, Ref. [35] argued that the EC paradigm can be paramount in that context and can present different solutions to decrease food waste. This requires practices and approaches that combine technological solutions, cultural and behavioral changes, and policy recommendations. Meanwhile, Geissdoerfer et al. [36] synthesized the similarities, differences, and relationships between CE and sustainability in an extensive literature review. The authors highlighted the fundamental importance of these two concepts for academia, the industry, and policymakers worldwide. Thus, CE can contribute towards improving agri-food chains in terms of performance and sustainability.

At a national level, research has focused on other agri-food chains. For example, Ref. [37] identified opportunities for improvement within CE in the agri-food chain of organic fine aroma cocoa in the province of Manabí. This research defined the prospects for development in Ecuador. Another agri-food chain evaluated was the plantain chain, which is considered one of Ecuador's most important agricultural products. This study maps the links and key products consumed by clients in that agri-food chain. To help farmers determine decisions, CE is analyzed. It is found that plant and fruit residues could be used to make new products [38].

1.1. Objectives

This study aims to evaluate the potential of implementing the circular economy in the pitahaya agri-food chain in Ecuador, as well as to compare the results with other agri-food chains evaluated in developing countries. An additional goal was to propose improvement perspectives based on CE for the agri-food chain of the pitahaya sector in Ecuador, focused on reducing and valorizing food loss and waste.

The scope of the research is to try to understand the contribution of CE to reduce the environmental impacts of current agri-food economic systems through a case study developed in the Ecuadorian Amazon region.

1.2. A Brief Description of Pitahaya

Pitahaya originated in North America (Mexico) and also the northern part of South America. It is known that, by the 13th century, indigenous people were consuming and appreciating pitahaya [39]. The fruit has its beginnings in semidesert areas. Specifically, yellow pitahaya is native to several tropical or subtropical countries, including Bolivia, Brazil, Colombia, Ecuador, Peru, and Venezuela. In comparison, the countries that commercialize it the most are Israel, Colombia, Taiwan, and Ecuador. The number of pitahaya species varies between 1500 and 2000, with the most traded ones belonging to the genera *Hylocereus* and *Selenicereus*. The fruits are also known as pitahaya [39,40].

The yellow pitahaya (*Selenicereus megalanthus*) is a tropical fruit with particular characteristics. Its shape is oval; the yellow shell is covered in scales, while its pulp (white, soft, consistent, and foamy) contains small seeds that, along with the pulp, are edible, resulting in one of the sweetest fruits found in nature. It is also known as scaly fruit or "dragon's heart" in Ecuador's subtropical and Amazonian regions [41].

The antioxidant capacity of its seeds is attributed to its high content of natural fatty acids, as well as 64.5% linoleic acid, 13.9% oleic acid, and 14.4% palmitic acid [42]. Of these, linoleic acid is the most important because it functions in the body as a buffer, capturing cholesterol and generating a cardiotonic effect [43].

Other important compounds present in the peel and pulp of this fruit are betalains, which belong to the bioflavonoids derived from quercetin. They are present as red and yellow indole pigments [44]. The structural diversity possessed by these pigments allows solubility in water, forming two structural groups: violet–red (betacyanins) and orange–yellow (betaxanthins). These are vitamin-like substances that work together with antioxidants such as vitamin C to prevent premature cell death [44].

Regarding plant residues, a study by Verona-Ruiz et al. [45] determined that the pitahaya stem has the following composition: crude protein (1.8–24.49 g), crude fiber (7.86–14.79 g), ash content (between 10.80 and 14.90 g), and ether extract (0.64–1.46 g), all expressed on a dry basis (g/100 g of dry matter). In addition, one pitahaya variety (*Hylocereus undatus*) has important amounts of Zn (34.02 mg/kg) and K (4.82 mg/kg).

1.3. Description of the Stakeholders and the Productive Process of the Pitahaya Sector in Palora Canton, Ecuador

On 22 June 2018, the National Service of Intellectual Rights (SENADI for its acronym in Spanish) declared the Palora Amazonian pitahaya as the fifth Ecuadorian product to achieve the recognition of the Denomination of Origin [46]. To meet this goal, the main stakeholders had to be producers, marketers (with local and export permits), and sellers.

Production: The fruit harvest starts when 18 months of growth have occurred and has an annual increase of 3000 kg/ha/year. This is until it reaches an annual fruit yield of 10 tons [30]. The main activities are described below.

Stage 1. *Pre-cultivation/land clearing* includes tutorship, seed selection, and land preparation. The tutorship system used on the farm studied is individual or traditional, where each post is placed at a planting distance of 3.0 m $\times$ 2.0 m to 2.5 m between each plant, for an approximate number of 1000 plants per hectare. Then, seed selection is performed by cutting the branch or pod (seed). Soil preparation is based on clearing the soil of stones and other debris that hinder the development of seedlings. This activity is complemented by draining the soil (if necessary) and plowing it to provide oxygenation and softness to the soil and, at the same time, allow the plant greater opportunities for development. Site preparation includes weeding and weed control with herbicides (at a rate of 3.5 L of glyphosate/ha), as well as machinery that consumes fossil fuels [30].

Stage 2. *Planting* involves seeding and resowing, replanting, pruning, fertilization, and chemical control. Sowing is performed directly with stems approximately 60–85 cm long, previously disinfected. Pruning is then carried out, this being one of the most necessary activities as it keeps the plantation in optimal conditions. Generally, three types of pruning are carried out on the crop: training, thinning, and phytosanitary. Fertilization is carried out in the edaphic and foliar form [30]. In the former, fertilizers are applied to pitahaya plants, mainly nitrogen (urea) and ternary fertilizers (16% N, 8% P_2O_5, and 12% K_2O). In addition, various chemical inputs are applied, mainly insecticides, acaricides, fungicides, and herbicides for weed control [30,47].

Stage 3. The *harvest and postharvest* include transportation, cooling, disinfection/cleaning, drying, packaging, and storage. Transport from the field to the collection center is carried out to avoid damaging the fruit. Once the fruits are transported to the processing plant, the cooling process is executed, where the fruits are immersed in cold water with detergent and carefully washed [30].

Then, disinfection is performed. The fruits are immersed and washed in a mixture of 150 mL of sodium hypochlorite dissolved in 300 L of water. Once the fruits are disinfected, they are selected according to their homogeneous shape (round or oval), uniform size, average weight, degree of ripeness, distribution of bracts, and sanitary aspect. According to their classification and weight, they are then individually packed in polyethylene nets and placed in cardboard boxes for storage until distribution and sale.

Market: Currently, according to data from the Ministry of Agriculture, the canton of Palora has the largest production of pitahaya (89.57% comprising 2000 hectares out of 2223 total hectares in the country) and has about 1500 producers. According to BCE statistics [48], it occupies an important place in the export of nontraditional fruits and, in recent years, has had a great performance in shipments abroad. In the high production season, between 5 and 10 million kilograms are produced, and exports from 2016 to 2020 have grown from USD 6 million to USD 60 million [49].

Foreign trade statistics [48] mention that, in 2019, Ecuador exported the fruit to 17 different countries. The United States and Hong Kong in China were the main export destinations, with approximately 51% and 36%, respectively. In that year, 7498.80 tons were exported, representing more than 44 million USD of income for the country; as mentioned above, 2020 exports exceeded USD 60 million. These figures denote the importance of the fruit in international markets and that there are opportunities for expansion [48]. Ecuador has already begun to export to Europe, as of 2021 [49], and exports are expected to increase in the coming years with the growth of markets in China and Russia.

Economics: As a perennial fruit, pitahaya requires a period of establishment or initial investment before the crop stabilizes production and yields profits for producers. According to the “Manual del cultivo de pitahaya para la Amazonía Ecuatoriana” published in 2020 by the “Instituto Nacional de Investigaciones Agropecuarias” [47], annual costs per hectare of pitahaya for the Palora area fluctuate between USD 5015 and USD 6935. Table 1 shows a breakdown of investment amounts for each stage of crop and fruit production in the region by live tutors.

Table 1. Investment in 1 ha of pitahaya, a live stakes system in Palora, Ecuador.

Item	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Land preparation	585	-	-	-	-	-	-	-
Planting	1253	-	-	-	-	-	-	-
Trellising	1180	-	-	-	-	-	-	-
Weed control	660	720	720	720	720	720	720	720
Insect control	140	540	1080	1080	1080	1080	1080	1080
Disease control	150	600	840	840	840	840	840	840
Fertilization	1340	2495	2960	2960	2960	2960	2960	2960
Pruning	480	585	585	585	585	585	585	585
Harvesting	-	75	750	750	750	750	750	750
Total cost	5788	5015	6935	6935	6935	6935	6935	6935

Source: [47].

The values shown in Table 1 show the cost of production for each stage of cultivation and harvest. As can be seen, 8 years of cultivation were considered, in which income starts in the second year given that there is no fruit harvest in the first year. In order to estimate the cost of production, the reference years used were 2012–2019 and are in ascending order; for example, year 1, the first year of cultivation, refers to the year 2012. From these values, taking into account the average selling price per kilogram of fruit (USD 2) and an estimated yield of 18,922 kg/ha from the fifth year of establishing the crop, the financial indicators show a net present value of USD 21,2233, an internal rate of return of 110%, and a benefit/cost ratio of 3.31 [47], which denotes the economic feasibility of the crop in the region.

2. Materials and Methods

The research was conducted from 2019 to 2021 at a pitahaya agri-food chain in Palora canton, Morona-Santiago province, Ecuador. It was descriptive–explanatory because it identified the stakeholders that composed the links that in turn determined the network and the production process. The CE was diagnosed following the criteria of the checklist by Dieguez et al. [31].

The main criteria used to elaborate the checklist were grouped in the conceptual basis of the European Union’s CE Action Plan [2] and previous research carried out worldwide (including studies in Latin America and other developing countries). A total of 91 items was compiled and evaluated by seven experts on the subject under study and was included in the Supplementary Material (Supplementary Table S1). In total, as a result of the consensus matrix, the variables defined were: source or supply of materials (D1), design (D2), manufacturing (D3), economic circle (D4), distribution and sales (D5), consumption and use (D6), 4R (D7), remanufacturing (D8), and sustainability (D9). Most of the studies formed groups of several indicators for each of the dimensions. A brief description of the criteria addressed and documents consulted in each of these dimensions is shown below.

Source or supply of raw materials (D1): This dimension included 12 criteria such as sourcing of materials and raw materials produced with lower environmental impacts, green sourcing, the presence in the chain of strategies focused on material substitution, and approaches to negative externalities. Criteria were extracted from [9,50–53].

Design (D2): This category included eight items that addressed approaches to environmental impacts throughout the product life cycle, product eco-design including strategies for repair, refurbishment or recycling, an approach to design for modularity, design for disassembly and recycling, and product reduction strategies. Many of the elements discussed in [50,54–58] were grouped together.

Manufacturing (D3): This dimension addressed five items, including energy efficiency in manufacturing/production, material productivity, reproducible and adaptable manufacturing, and use of certified materials. The main documents consulted were [6,54,57,59,60].

Economic circle (D4): This included 10 items such as potential investment facilities when alternative products/energy were reused, economic taxes due to the presence of ecological policies, profit margins based on costs and prices, leverage, investment recovery and capital expansion, and balance between assets and liabilities. Some of the bibliographic sources consulted were [52,53,57,58,61,62].

Distribution and sales (D5): This dimension had the greatest weight upon evaluating the agri-food chain. It included 20 of the 91 items analyzed that were directly associated with the chain. Some of them were optimized packaging design, redistribution and resale, participation in value chains, knowledge exchange with suppliers and customers, close collaboration between involved parties, certifications of customers and suppliers, and the presence of mechanisms/equipment to guarantee the traceability of a product, among others. Some of the bibliographic sources consulted were [6,53,54,62].

Consumption and use (D6): This dimension focused on the reuse of products towards engaging in a circular economy. It considered nine items, including community participation, ecolabeling, reuse, the presence of multipurpose space, campaigns or incentives towards socially responsible consumption of the product, and the use of electronic media (virtualization/dematerialization). Some of the sources used were [4,50,63].

4R (D7): This dimension included 17 checklist items and addressed four environmental axes focused on collecting, disposal, recycling, and recovery. Some of the aspects addressed were: extended producer responsibility, separation of components, use of by-products, reuse, renewal and recycling, downcycling and upcycling, energy recovery, and valorization of organic fractions. These items were documented from sources [4,64–70].

Remanufacturing (D8): This dimension included five items covering refurbishment/reconstruction, maintenance, after-sales service, and the lifetime of equipment and products. The main documents consulted were [50,59,70].

Sustainability (D9): This dimension included five items (sustainability over time, environmental safety, gender equity, economic viability, and social–cultural sustainability). The main bibliographic sources referred to were [36,67,71,72].

The scale variables that determined the level of CE of the supply chain and company were calculated using Equations (1) and (2) [31]. In the case of Equation (1), the 91 items on a Likert scale were consulted for determination.

$$\mathrm{CEL} = \frac{\sum_{j=1\ \forall j \in m}^{n} \mathrm{CEL}_j}{n} \quad (1)$$

where:

CEL: Scale variable that determines the level of circular economy of a supply chain *m*, seen as the average of the CEL of all the companies *j* that compose it.

m: Nominal variable that identifies the supply chain.

j: Nominal variable that identifies the company belonging to supply chain *m*.

E_{kj}: Ordinal variable measured on a Likert scale from 1 to 5 (Very low = 1; Low = 2; Medium = 3; High = 4; Very high = 5), where k corresponds to the 91 items in the checklist. k = {1, 2.... 91}, grouped by each dimension.

Equation (2) determines the level of circular economy calculated for the company or sector (NEC_j) based on the results of the dimensions and variables previously obtained.

$$CEL_j = \sum_{i=1}^{9} (w_i \times D_{ij}) \quad (2)$$

where:

CEL_j: Scale variable that determines the level of circular economy calculated for company j.

w_i: Specific weight determined for each dimension D_i.

D_{ij}: Scale variable calculated from the mean of the corresponding E_k.

A hierarchical analysis (weights method) proposed by Saaty [73] was used to obtain each variable's weights. In this case, the procedure was based on a square matrix constructed according to the number of criteria to be weighted that were compared pairwise [31].

The CEL evaluation criteria obtained from the scale variables were categorized according to the scores obtained for each of them. The interpretation intervals for the CEL variable in this case were: very low (1.5), low (>1.5 and 2.5), medium (>2.5 and 3.5), high (>3.5 and 4.5), and very high (>4.5). These numerical values allowed the state of the object of study to be compared with other national and international benchmarks to promote its development. Additionally, several statistical criteria were considered, such as the mean values and standard deviations obtained for Ek and *Di*, which better described the CEL variable's behavior.

Once the stakeholders of the chain were checked, critical points were identified and strategies were proposed to increase the chain's competitiveness, improve environmental performance, and promote a circular economy in the context of the chain.

3. Results

Circular Economy Evaluation in Pitahaya Cultivation, Palora, Ecuador

The checklist by [31] was applied. Table 2 shows the general results of the evaluation of EC in the pitahaya production chain in the canton of Palora. The dimensions were identified from highest to lowest weakness, i.e., supply of materials/raw materials, remanufacturing, and distribution and sales (with a median ~1.7), followed by design, 4R, and consumption and use. In these criteria, the main difficulties in CE implementation were identified.

Table 2. Statistical parameters for the evaluation of CE in the Pitahaya agri-food chain, Palora, Ecuador.

No.	Criterion	Mean	SD	Min.	Median	Max.	Evaluation
1	Supply of materials/ Raw materials	1.66	0.16	1.42	1.72	1.83	Low Level
2	Design	1.99	0.15	1.85	1.93	2.2	Low Level
3	Manufacturing	2.57	0.13	2.4	2.6	2.75	Medium Level
4	Business cycle	2.44	0.14	2.3	2.45	2.6	Medium Level
5	Distribution and sales (chain)	1.72	0.17	1.45	1.75	1.9	Low Level
6	Consumption and use (reuse of products)	2.23	0.15	2	2.2	2.4	Low Level
7	4R	2.13	0.12	2	2.1	2.3	Low Level
8	Remanufacturing	1.69	0.19	1.4	1.75	1.9	Low Level
9	Sustainability	2.78	0.11	2.65	2.75	2.95	Medium Level

Table 2 shows the main descriptive statistical parameters.

Upon analyzing the stakeholders' perceptions, for example, regarding the source or supply of materials or raw materials, different difficulties were identified, mainly with the energy indicators. The companies involved in this activity did not implement energy production from by-products and process residues (here, the valorization of biomass could provide a strong contribution). On the other hand, there were no green procurement strategies for the goods acquisition process, no life cycle assessment, no quantification of emissions and relevant resources consumed, and no impacts related to the environment, health, or resource depletion. Additionally, there were no strategies focused on substituting imported materials for local products or renewable materials, so the dimension had a low level.

The economic circle achieved a median of 2.45, while the dimensions with the best scores were sustainability and manufacturing (medians of 2.6 and 2.75, respectively). In the former case, it must be associated with the fact that the different stakeholders had a positive perception of sustainability over time and of economic viability. The crop generated important economic benefits. The stakeholders involved in the activity (farmers, local marketers of agricultural inputs, local fruit marketers, fruit sellers, and exporters) received a good income for some years, while the projects, as perennial fruit, had an extended useful life. In addition, most of the people involved had experience in agricultural activities. In terms of the source of income and sustainability, there were no other livelihoods in the area that competed with the activity. Other activities included cattle ranching (with low milk and meat yields) and illegal mining (with serious environmental impacts and health risks).

The highest results from the evaluation of stakeholders' CE levels were between one (very low) and two (low). This represents a low indicator value for the chain. In summary, Figure 1 shows the strengths and weaknesses of the criteria evaluated, with 3.3% strengths, 18.68% acceptable aspects, 21.98% weaknesses, and 56.04% severe weaknesses. These results were comparable to those regarding the Mexican cocoa agroindustry published in [31], where 71% of the criteria were weaknesses and severe weaknesses. They also coincided with results for the organic cocoa network of Manabí (Ecuador) that identified weaknesses of 8% and severe weaknesses of 64%, while 11% were acceptable aspects and 17% were strengths [37].

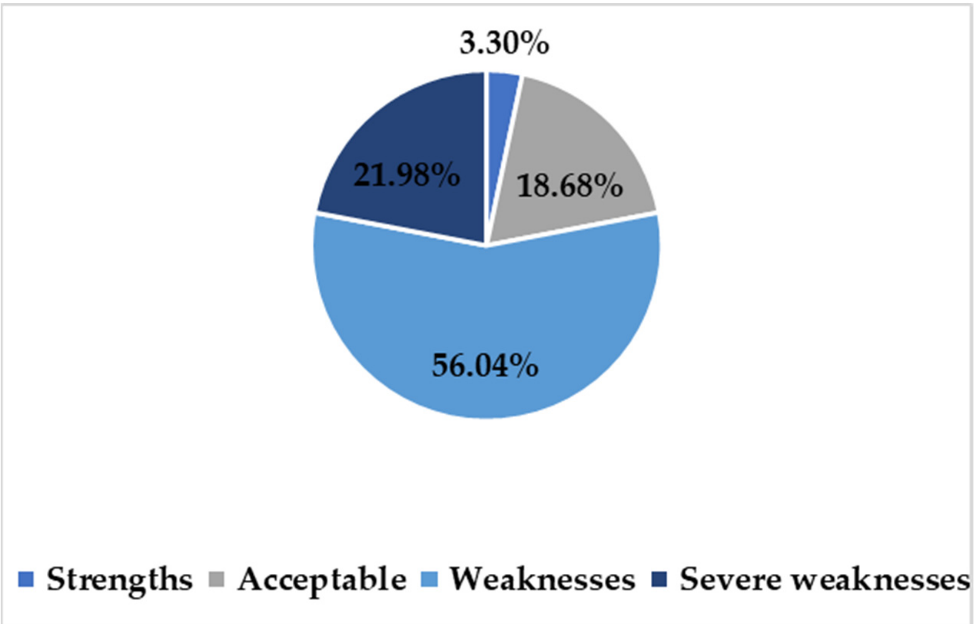

Figure 1. Results of the circular economy's strengths, acceptable aspects, weaknesses, and severe weaknesses for the object of study.

4. Discussion

4.1. Comparative Analysis of the Application of the Circular Economy to Other Agri-Food Chains

The comparison of the study with other cases of application of the CE assessment tool for agri-food chains can be seen in Table 3. These studies focused on other sectors in

Ecuador and Mexico, for example, the coconut chain [31], the cocoa chain (conventional and organic farming) [37], and the banana chain [38]. The latter two were recent studies performed in the province of Manabí, Ecuador. In summary, they were compared with four other case studies carried out in the two aforementioned countries.

Table 3. Comparison of the results of this study with other cases of evaluation of CE in agricultural production chains.

No.	Criterion	Cocoa Chain, Mexico	Organic Cocoa, Manabí, Ecuador	Coconut Chain, Manabí	Banana Chain, Manabí	Pitahaya, Ecuador
Reference		[31]	[37]	[31]	[38]	This work
1	Source or supply	2.54	2.06	1.09	2.63	1.72
2	Design	2.25	2.69	1.40	2.88	1.93
3	Manufacturing	2.80	1.30	1.81	2.83	2.60
4	Business cycle	3.50	2.00	2.39	2.68	2.45
5	Distribution and sales	3.23	2.98	1.39	2.72	1.75
6	Consumption and use	3.22	1.19	1.46	2.66	2.20
7	4R	2.94	1.64	1.30	2.69	2.10
8	Remanufacturing	2.80	1.00	1.01	2.93	1.75
9	Sustainability	3.50	4.03	2.21	2.94	2.75
-	Total (9 indicators)	2.98	2.10	1.56	2.77	2.14

The overall results (total of the nine indicators) presented in this agri-food chain (2.14) were higher than those of the coconut (1.56) and organic cocoa (2.1) chains in Manabí province, but lower than those of the cocoa chain in Mexico (2.98) and the banana chain in Manabí (2.77). Our analysis of the nine indicators produced lower results than the last two chains mentioned, which was reflected in the weight of the final evaluation.

A comparison with the organic cocoa chain in Manabí showed that, despite having a slightly lower value in the evaluation, this chain had three indicators that yielded better results (design, distribution and sales, and sustainability). However, the weighting of the indicators manufacturing, remanufacturing, and consumption and use in this chain was much lower than in the pitahaya chain. This may be associated with the production deficiencies of the cocoa processing plant raised by [37]. In our case, as discussed above, many difficulties in the sector need to be pointed out and addressed on several fronts. In the next section, some strategies that could contribute to boosting CE in the pitahaya sector in Palora canton were presented. Regarding sustainability (Criterion 9), despite the results being the highest of the nine indicators, they were still low. Our results were higher than those shown in the coconut chain in Manabí and lower than those presented in the cocoa and banana studies [38].

4.2. Prospects for Improving CE in the Pitahaya Sector's Agri-Food Chain in Ecuador

The above aspects of the evaluation showed that the chain should focus on several fronts, mainly on fostering the relationship between stakeholders, the diversification of production, and a focus on CE, incorporating multi-R strategies and waste valorization. This would increase added value, create jobs, and reduce the environmental and social impact of the sector.

In circular economy assessments, sourcing, design, and manufacturing indices were generally deficient. (See the previous section). In the cultivation stages, we proposed an increase by establishing a detailed analysis of raw material suppliers and defining policies for the procurement of raw materials of high quality. Another recommendation is to seek advice on pest management, chemical products, and occupational safety in the cultivation stages. In addition, more training should be provided in techniques for planting, trellising, turnover, harvesting, transportation, and post-harvesting in the fruit processing facilities.

To strengthen the indicators (economic circle, distribution and sale, and consumption and use), producers should be encouraged to collaborate so that, together, they can receive fairer prices (mainly in export chains) and strengthen high-value pitahaya chains at a national level.

At the end of the investigation period, prices decreased. The restrictions generated by the COVID-19 pandemic along with the increase in time and costs of the logistics chains had affected the export chain, and large quantities of fruit could not be exported. Many producers expressed their concerns about the difficulties of exporting and lower prices, the impact on supply chains, and labor difficulties during the high peaks of infection in the region and during periods of mobility restrictions to prevent the spread of COVID-19 (Ecuador declared a state of emergency on 16 March 2020, and it was in force for 6 months, during which time mobility was restricted) [74].

The difficulties of supply chains have been exposed in recent literature on the subject. As stated by [75], the COVID-19 pandemic affected global supply chains at an unprecedented speed and scale, mainly in emerging economies. In turn, agricultural systems experienced a drop in income, production losses due to difficulties in marketing through conventional channels, and limitations in cropping systems management due to reduced access to inputs and labor [76]. It is also documented that some food supplies were suspended due to restricted demand, closure of food production facilities, and financial constraints [77]. These circumstances imply immediate and significant socioeconomic consequences for local producers.

A critical point identified was related to certifications. Few producers had certifications; of the 1500 producers, only 50 had good agricultural practices certifications [49]. The applicability guide for the pitahaya production line is the voluntary General Guide on Good Agricultural Practices Certification [78]. The process helps protect the environment and establishes better working and safety conditions for workers involved in the production chain [47].

Furthermore, the 3R variables—disposal, remanufacturing, and sustainability—could be implemented. These contribute to or are related to the above elements. Fruit sector chains, such as the case of pitahaya, could play an important role under the circular economy approach, mainly in the valorization of waste from each stage of the productive activity [79]. The generation of large amounts of waste and by-products “on or off the farms” contributes to environmental stress. However, as El-Chichakli et al. [80] put it, several high value-added products can be obtained by recycling these waste products. These can contribute to the achievement of carbon neutrality and the attainment of the UN Sustainable Development Goals [81]. Organic residues from pitahaya cultivation can be a source of bioactive compounds, reused and revalued through various applications.

Food waste can be used as feedstock in biotechnological processes. Through chemical and biological methods, food waste is hydrolyzed into glucose, free amino nitrogen, and phosphate, which are usable as nutrients by many microorganisms whose metabolic versatility allows the production of a wide range of products and become an additional option for green chemical technologies [82]. They can also be used for wastewater treatment. The review in [83] examined the specific potential of food waste components as adsorbents for the removal of toxic dyes from polluted water. This review aimed to highlight the valorization of food waste materials to remove dyes from polluted waters; thus, ensuring long-term sustainability.

What is more, food waste has been widely used in the energy sector as various bio-based liquids or gaseous fuels. Bioenergy is known for its importance and potential, including biofuels and biomass [84,85]. This is seen as a solution that can address future shortages and rising fossil fuel prices. Specifically, crop/processing residues are estimated as the second generation of bioenergy. They have been gaining global recognition for their potential to provide sustainable bioenergy (avoiding competition between energy and food production) [86]. Even food waste has been treated in anaerobic digestion with a high rate of organic loading [87]. Furthermore, the review of [88] analyzed the current status of available technologies used in the disposal of food waste in order to identify process intensification variables for converting it into fuel, taking into account environmental concerns and logistics of utilization. The main technologies include incineration, landfilling, composting, anaerobic digestion, pyrolysis, and biochemical methods, along with recent developing technologies such as hydrothermal carbonization and supercritical water gasification [88]. Another application in energy is the use of food waste for green energy vehicles in the form of fuels to be used in internal combustion engine vehicles (running on biomethane or bioethanol), fuel cell vehicles (biohydrogen), and plug-in electric vehicles using bioelectricity [89]. These papers reflect the various technological routes and applications for energy recovery from food waste. Pitahaya residues and by-products contain significant amounts of carbon and macro- and micronutrients, which could be used to generate bioenergy.

In the case of agri-food by-products for animal feed, it is an old practice that can be considered a potential strategy to decrease the ecological and water footprint associated with crop waste [90,91]. The work of Castrica et al. [92] presents a technical evaluation of a case study and analyzes the potential application of the process in the European Union within the current legal framework. In addition, the presence of bioactive phytochemicals in these residues provides added value to animal health [93]. For example, the positive effect of polyphenols from agro-industrial wastes on the oxidative status of wetlands has been demonstrated [94]. Moreover, in the case of ruminants, they have the unique ability to utilize fiber due to their ruminant microbes. Therefore, cereals can be replaced with these residues [95].

In relation to the waste source, composition, moisture content, and C/N ratio of the process residues, some fractions are conducive to composting [96,97]. The residues can be used once they are mixed with other waste fractions. For example, [98] obtained high-quality compost from different combinations of fruit waste (apple, banana, orange, and kiwi peels) and vegetable waste (cabbage leaves, potato peelings, and carrot peelings) with sawdust. In addition, the process of composting fruit and vegetable waste creates a vital source of organic matter that is important in retaining soil nutrients and moisture, preserving soil fertility, and improving the physical and chemical properties of soils [99]. Other emerging conversion methods, such as dehydration, biochar production, and chemical hydrolysis, may also show promise in allowing food waste to be used in agriculture and soil remediation. Overall, the valorization of food waste into biofertilizers and soil amendments can contribute to combating land degradation in agricultural areas [100].

On the other hand, many agri-food chain by-products [101], such as those found in fruit and vegetable processing, provide an important source of bioactive compounds (fiber, antioxidants, and prebiotics). They can be incorporated to develop functional foods [102]. For instance, solid fruit and vegetable waste from isotonic beverages are used to produce functional cookies and cereal bars with high fiber and mineral contents [103]. Díaz-Vela et al. [104] documented a similar process with prickly pear and pineapple peel flour incorporated into cooked sausages inoculated with lactic acid bacteria. This process improved the thermostability of the lactic acid bacteria in this food during storage. Specifically, pitahaya is similar to the prunus *Opuntia ficus-indica*, so pruning residues could be attractive sources for developing new functional foods.

Dissimilar to functional foods, nutraceuticals are healthy products created from foods that are formulated and consumed in defined doses in a drug or medicine format [105]. Thus, the rich composition of fruit waste may be suitable for developing nutraceuticals as an alternative to synthetic substances [106]. To this end, many conventional and emerging technologies are used to extract bioactive compounds from agro-industrial wastes for nutraceutical development [107]. The medicinal properties of the fruit mentioned above are also in the discarded fruits, allowing people to use them for nutraceutical development.

In the case of cosmetics, there is a marked trend in the industry towards the development and manufacture of high-value products from natural sources. The consumers of these products, who are now aware of the concepts of a circular economy and sustainability, are looking for “green” products. In this sense, bioactive compounds extracted from food by-products, for instance, phytonutrients, microbial metabolites, dairy-derived active ingredients, minerals, vitamins, or animal proteins, can benefit the skin, giving rise to new products with high added value, such as cosmeceuticals [108]. The most commonly reported ones are bioactive phenolic compounds due to their photoprotective and antioxidant properties [109]. The pitahaya fruit's vast composition of phenolic compounds and its antioxidant capacity were mentioned above.

In general, it is necessary to encourage better production practices that increase yield and quality, including safety criteria for workers and environmental protection.

5. Conclusions

The conceptualization of CE in agri-food chains is a crucial and novel topic. It includes aspects ranging from improving the efficiency of production systems to the actors' social and behavioral aspects. In this research, the pitahaya agri-food chain was selected as a case study to evaluate the potential for implementing CE in agri-food supply chains. Pitahaya production in the canton of Palora is one of the main economic activities in the Ecuadorian Amazon region. Pitahaya is exported to several countries and, in recent years, has become an important source of employment and economic income for the country. Therefore, the key actors in implementing CE concepts in this system could play an important role in the agri-food chains of Ecuador's Amazon region.

This research identified the actors, analyzed the links between stakeholders in the system, and established criteria for the conceptual model of the pitahaya producer supply chain in connection with the CE concept. The total indicator (CEL) evaluated in the study had a low level (2.14 points out of 5), which implied that the situation is unfavorable and that improvements are required in the agri-food management of the cultivation and processing of the fruit. Only manufacturing, the economic circle, and sustainability had a medium level (2.6 points), while the rest were low (all below 2.5, specifically between 1.83 and 2.4). These results were comparable to other studies concerning the application of the assessment tool, denoting that many challenges remain in the productive national context for the implementation of CE.

The application of the CE evaluation tool to stakeholders in the pitahaya chain identified opportunities for improvement. We propose improving relations between producers and marketers, mainly in order to search for a better distribution of income. It is important to involve ministries, public policy-making entities, and others in making marketing–export mechanisms more flexible and establishing fair prices for producers all year round. Another distinctive element could be adopting good practices that could contribute to an increasing income, creating new value-added products, and improving environmental conditions. It is necessary to train the personnel of the actors in the object of study in basic competencies for the management of the circular economy and the chain.

Additionally, there were several future research directions based on the results. For example, as part of implementing various solutions to the case problem, multi-R waste valorization approaches could be promoted as a new source of income. Other possible future research projects should address various government incentive scenarios for producers and stakeholders within the chain, especially agricultural input suppliers. The implementation of incentives could probably minimize the cost of production for producers and, in turn, provide the opportunity to reduce the price at which they are sold in domestic markets.

In the context of Palora canton and the Amazon region, the implementation of a financing policy scheme with low-interest rates should be considered to boost the growth of the sector and improve the producers' farms. In addition, the pitahaya chain could be interconnected with other types of agri-food chains in the region to involve other actors with similar roles and exchange experiences. Finally, more research should be conducted on the concept of CE in the sector, mainly focused on the valorization of biomass as a contribution to the bioeconomy in order to contribute to the literature on the economic sector and contribute to growth in the country in the context of sustainability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14052950/s1, Table S1: CE evaluation checklist.

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