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Systematic Review

Circular Economy in Guaiamum and Uçá Crab Waste in Brazil: Potential By-Products—A Systematic Literature Review

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Abstract: This study aimed to fill a gap in the sustainable management of the reverse supply chain of Guaiamum and Uçá crab waste in Brazil, an endangered species. The study focused on the circular economy, governance, and recent developments, and identified circular economy practices in the utilization of solid waste from the fishing and collection of these species in extractive regions, in line with the United Nations (UN) Sustainable Development Goals (SDGs). A systematic literature review was conducted in major scientific databases. The selection of the 20 research publications followed pre-established criteria, including relevance to the SDGs and systematic review methodology. The results highlighted key variables related to the characteristics of by-products and the factors that influence the adoption of circular economy practices, in line with relevant SDGs. The most mentioned by-products include animal feed, organic fertilizer, biofuels, crab shell chitin biocomposite derivatives, as well as Chitosan-based composites for food packaging applications due to their non-toxicity, antimicrobial, and antifungal properties. The study also identified future research opportunities covering education, policy, and management, in line with the UN SDGs. This study emphasizes the importance of the circular economy for solid crab waste in Brazil, a country with 12% of the world's mangroves, which are essential both as a nursery for crabs and for ocean nutrition. It also analyzes current trends and initiatives in the reverse management of Guaiamum and Uçá crab waste, in the context of Supply Chain and Sustainable Management.

Keywords: circular economy; reverse logistics; waste; systematic literature review (SLR)

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1. Introduction

Although humanity has been experiencing significant technological convergence in recent years, hunger and food waste are still realities in many countries, to the point where the Food and Agriculture Organization of the United Nations (FAO) has expressed concern and is seeking mitigating measures [1]. One strategy that can be effective in tackling these challenges is the adoption of circular economy practices: a global trend that involves recycling, reuse, remanufacturing, sustainable supply chains, and measures that extend the life cycle of raw materials, avoiding resource scarcity and providing environmental sustainability [2]. In addition to issues related to hunger, there is a real concern about the accumulation of solid waste resulting from unbridled consumption, associated with the finiteness of many natural resources widely inserted in the industrial chain. In this respect, Viera [3] comments "Air, water, soil, sunlight, oil, minerals, CO_2... many of these resources are not infinite". Among these varied resources, there is a growing use of solid waste by-products from aquatic organisms, such as fish, mollusks, crustaceans, algae, and aquatic plants, for various purposes, such as food (human and animal), pharmaceuticals, cosmetics, biomaterials, and biofuels [4]. This practice is in line with the UN's Sustainable Development Goals, specifically SDG 12 (Sustainable Production and Consumption) and SDG 14 (Life in Water), the purpose of which is to promote sustainable production and consumption practices, as well as the conservation of aquatic ecosystems.

Mangroves are important ecosystems that play a vital role in protecting the coast from erosion and maintaining water quality. They are also important for fishing and collecting crabs, which are a source of food and income for many people around the world. One way to help protect mangroves is to adopt circular economy practices. The circular economy is an economic model that seeks to reduce waste and promote the recycling and reuse of resources. By adopting circular economy practices, we can reduce the environmental impact of fishing and crab harvesting and help protect mangroves.

Brazil has a vast mangrove ecosystem, which is extremely important in protecting the coast from erosion, maintaining water quality between limnic and marine systems, and is rich in biodiversity, playing a fundamental ecological role as a natural nursery for many species of fish and other marine animals. The natural resources of this ecosystem are heavily exploited by native activities, which include the extraction of resident animals for economic purposes, and especially by large entrepreneurs in the hotel sector, harbors, construction, and shrimp farming, among others [5]. As for native exploitation, although it generates local income, the population of artisanal fishermen is ranked among the poorest in the country and the world and is consequently food insecure [6].

Among the main fishing resources exploited are crabs, especially the Guaiamum -*Cardisoma guanhumi*- and the Uçá -*Ucides* cordatun s- which are very popular in Brazilian cuisine and therefore threatened with extinction in the country. In addition, they are recognized for their ecological importance in nutrient recycling and soil revolving, during the consumption of organic plant debris and the construction/maintenance of their galleries, respectively [7–9].

Guaiamum and Uçá crabs play an important role in the local and regional economy, generating significant solid waste for the environment. The production of this waste begins with crabbing activity, continues with transport (with the death of many specimens) sale, and ends, finally, as culinary waste [8].

In addition to culinary uses, chitin from the exoskeleton can be utilized for biomedical, cosmetic, and food uses, and the viscera can be processed for use in animal feed [9]. However, the application of the circular economy to crab waste is still little explored in Brazil.

Valorizing this waste can have a positive impact on these communities, offering alternative income and improving their socio-economic conditions [6]. In this context, the proper governance of this crab solid waste value chain is a relevant and current challenge, given that the intermediaries in the distribution process play a significant role in the crab supply chain, which starts with the crab picker right through to the end consumer. It is important to emphasize that these intermediaries have considerable bargaining power and often pay insignificant amounts to the pickers, corresponding to only a tiny fraction of what they get from commercializing the products. According to Willianson [10], a governance structure aims to guarantee coordination (with or without the market) that saves transaction costs and reduces uncertainty, compensating agents for limited rationality and opportunism. Also, Besanko et al. [11] state "This dynamic of the intermediaries in this production chain generates agency conflicts and has a negative impact on the socio-economic sustainability of the communities involved in crustacean fishing".

In the supply chain for these crustaceans, there is a pattern of raw material flow that involves different actors, including collectors, transporters, intermediaries, and, finally, distribution to the end consumer, whether through bars and restaurants or the processing of crab meat in industrial units for export or distribution in retail chains. However, it must be emphasized that, throughout this logistical process, the generation of waste is inevitable. On the other hand, the lack of an efficient system for treating and using this waste can result in negative environmental impacts and the loss of economic and social opportunities. To address these issues, sustainable supply chain management is essential. Adequate governance, combined with the implementation of circular economy practices, can help to reduce waste, valorize by-products, and improve the socio-economic conditions of fishing communities. In addition, it is important to seek strategies that promote equity in the distribution of value along the chain, ensuring that waste pickers receive fair remuneration for their work so that they can improve their quality of life [12].

In this study, we explore the potential of the circular economy to utilize and add value to the solid waste generated from crab fishing and harvesting in Brazil. We hypothesize that the adoption of circular economy practices could reduce the waste generation of these species, promoting environmental sustainability and bringing economic benefits through the valorization of by-products. We believe that awareness among the actors involved in the production chain and the implementation of public policies are fundamental to encouraging the adoption of these practices. Furthermore, we argue that collaboration between different actors is essential for the implementation of circular economy practices. These hypotheses guide our research on the possibilities of applying the circular economy to the waste management of Guaiamum and Uçá crabs, considering their environmental, socio-economic, and legal impact. In this study, we will use descriptors of sustainable practices and the circular economy to mirror the hypotheses in the analysis of results and discussions. This study will be based on these species, which are threatened with extinction and are more representative in socio-economic and environmental terms, due to their high consumption in Brazil and the volume of their population in the mangroves. Thus, the general objective of this study is to analyze circular economy practices and the valorization of crab waste in the Brazilian context, focusing on the Guaiamum and Uçá crab species, and their relevance to the UN Sustainable Development Goals. Specific objectives include: (1) Investigating the feasibility of adopting circular economy practices, including composting and flour production, for the management of Guaiamum and Uçá crab waste in the Brazilian context; (2) analyzing the opportunities for valorizing by-products from crab species, considering global studies on the production of biogas, brake pads, carbon materials, and other products from this waste; (3) researching how the awareness and engagement of fishermen, industries, researchers, and government bodies can influence the adoption of sustainable waste management and circular economy practices, in line with the Guaiamum and Uçá species; (4) evaluating the role of national and international public policies in promoting the adoption of circular economy practices and sustainable crab waste management, taking into account the protection of endangered species; and (5) investigating examples of collaboration between different actors, such as fishermen, industries, researchers, and government bodies, at national and international levels, to strengthen the governance of the production chain and promote sustainable practices.

2. Materials and Methods

2.1. Introduction to the Study Context

Mangroves are coastal ecosystems that play a key role in biodiversity conservation, erosion protection, and water quality maintenance. They also provide essential ecosystem services for human populations, such as fishing, tourism, and climate change mitigation. However, mangroves are threatened by various factors, such as deforestation, pollution, urbanization, and sea level rise. Brazil is considered the country with the largest area of mangroves on the planet. There are 25 thousand square kilometers, distributed along 7408 km of coast, from the extreme north of Amapá to São Francisco do Sul, in Santa Catarina [13] (See Figure 1).

This is equivalent to 12 percent of the world's mangroves [14,15]. Crabs represent the main economic activity of traditional human communities living around coastal mangrove regions. Among the species commercialized in Brazil are the Guaiamum -*Cardisoma guanhumi*-, the aratu *Goniopsis cruentata*, the crabs *Callinectes*, and the mangrove crab *Ucides cordatus*. The latter is the most important species for the economy of riverside populations [14,15]. The main Brazilian fishing regions for crabs, although they are not the main consumers of the meat, are as follows: Salgado, in Pará, the Parnaíba delta, between Maranhão and Piauí, the entire state of Sergipe, the Guanabara and Sepetiba bays, in Rio de Janeiro, and the Iguape and Cananéia mangrove swamps, on the southern coasts of the states of São Paulo, Paraná, and Santa Catarina [16]. The amount of wastage in the crab harvesting process in the Parnaíba Delta alone in Maranhão/Brazil is noteworthy: reports from traders show that crab losses in bars and restaurants are due to poor reception and storage conditions, increasing wastage by around 20% to 30% [8].

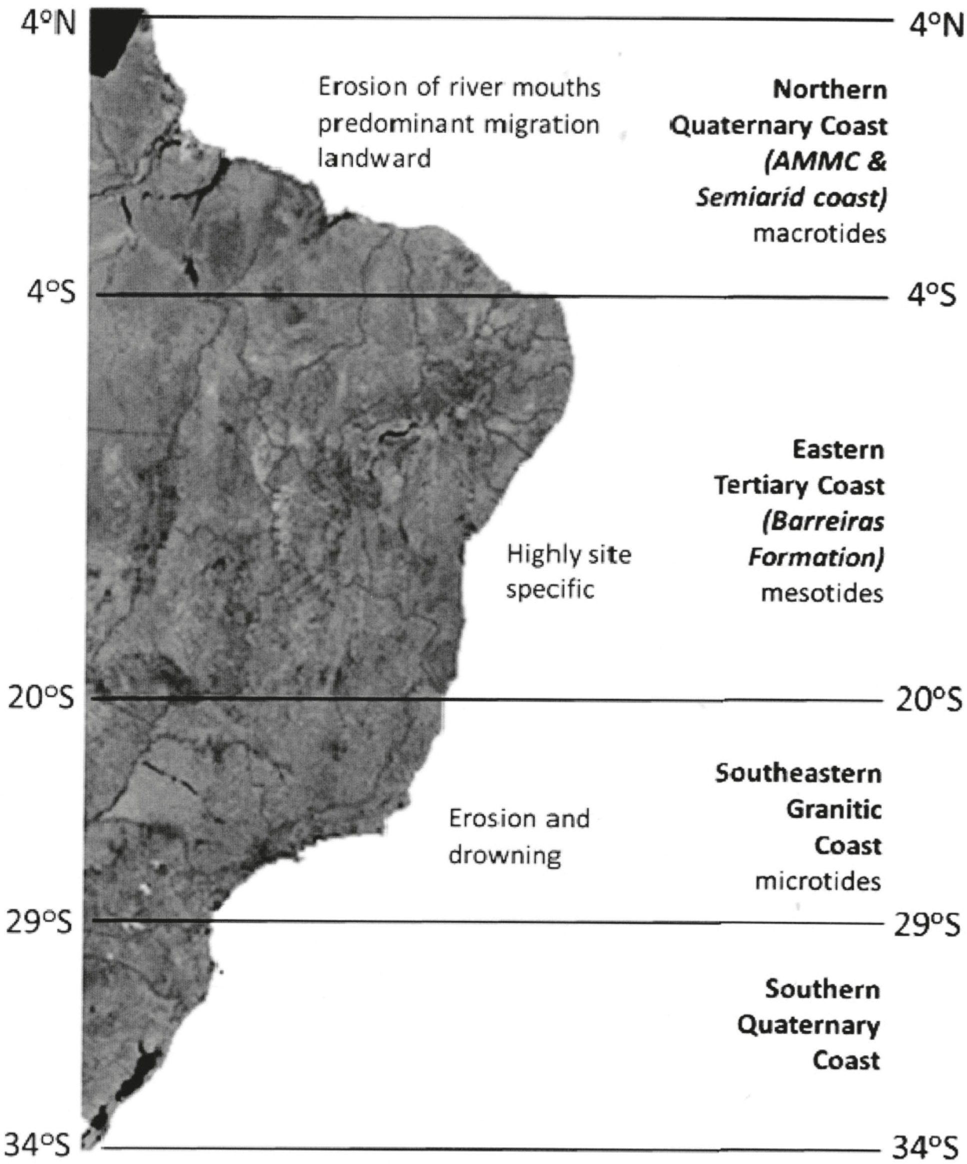

Figure 1. Map of the mangrove area in Brazil [13].

2.2. Circular Economy and Solid Waste Management

Waste management plays a key role in the circular economy, an overarching concept that seeks to redesign processes, products, and consumption to maximize the reuse of resources [17]. In this model, the generation of waste is the end of each chain, be it extraction, production, or final consumption. What was once considered waste should be considered a resource and raw material for another process [18]. Waste management, therefore, is an essential approach to minimizing the amount of waste disposed of and finding ways to turn it into valuable resources for other production processes. In the circular economy, waste management plays a crucial role in promoting sustainability, both in the production process and in consumption [19]. By adopting appropriate waste management practices, it is possible to preserve natural resources and delay their depletion. On the other hand, waste management contributes to reducing waste production and greenhouse gas emissions, promoting significant environmental benefits. In Brazil, the measures adopted to manage waste in the circular economy include selective collection, recycling, composting, remanufacturing, reusing products, and encouraging conscious consumption, which was introduced by federal legislation in 2010 [20]. These practices aim to transform the production chain into a continuous cycle of consumption, guaranteeing the preservation of natural resources at all stages. The benefits resulting from this approach are diverse, including reducing waste, mitigating climate change, creating jobs, economic sustainability, reducing pollution, and improving quality of life [2].

In the case of solid waste management for Guaiamum and Uçá crabs in Brazil, the circular economy can be applied by utilizing the by-products of these animals, which are often discarded or not used. By sustainably using these by-products, whether in the production of animal feed, composting, or other industrial processes, the circular economy can help reduce waste and generate new sources of income for local communities. In addition, the application of the circular economy can contribute to preserving the environment and promoting sustainability. Therefore, even if there are losses of crabs before final consumption, applying the circular economy to the management of solid waste from these animals can be a viable and sustainable alternative to reduce waste and generate value from often neglected by-products. It is important to emphasize that the circular economy is a strategy that contributes to achieving the SDGs by promoting waste reduction and more efficient use of natural resources. According to The Circularity Gap Report, carried out by Circle Economy, a group supported by the United Nations (UN) Environment agency [21,22], only 9% of the global economy is circular today, which means that the planet reuses less than 10% of the 92.8 billion tons of minerals, fossil fuels, metals and biomass consumed annually in production processes. The report emphasizes that, due to the greater efficiency in the use of resources, resulting from the practice of recycling, reuse, and remanufacturing, there is great potential in the circular economy to combat climate change, as well as to stimulate economic growth.

2.3. Governance of the Sustainable Solid Waste Supply Chain

The crab supply chain in the Parnaíba Delta is an example of how the absence of governance in a supply chain impacts inefficiency: crabs are caught in precarious conditions, transported in inadequate conditions, and stored in unsanitary conditions. As a result, a large quantity of crabs is lost along the supply chain. Catching crabs in the Parnaíba Delta is carried out by artisanal fishermen (See Figure 2a). The fishermen use nets to catch the crabs, and the crabs are then placed in jute bags. The jute bags are then transported to the landing sites, where they are sold to middlemen [23]. The middlemen buy the crabs from the fishermen and resell them to wholesalers. The wholesalers transport the crabs to markets in Teresina, Fortaleza, and other cities. The crabs are then sold to restaurants and bars. The crabs are transported from the Parnaíba Delta to the large consumer markets by lorry. The trucks are loaded with around three or more tons of crab, and the crabs are piled up in heaps of around 1.8 m (See Figure 2b). The crabs are not refrigerated and are transported for around 350 to 500 km. As a result of the precarious transport conditions, a large number of crabs are lost along the supply chain. Reports obtained from traders show crab losses in bars and restaurants due to poor reception and storage conditions, increasing waste by around 20% to 30%. The way live crabs are transported between the landing sites in the Parnaíba Delta and the major consumer markets causes losses estimated at 40% to 60% [23,24].

MMA [25,26], Ordinance 45/2014, and 161/2017 set out the national list of endangered species of Brazilian fauna. On this list, the guaiamum -*Cardisoma guanhumi*- is classified as a "Vulnerable" species, which means that it is at risk of extinction in the medium term, requiring effective action for its conservation and protection. Consequently, the Guaiamum is considered an endangered species. The *Ucides cordatus*, known as the Uçá crab, is also on the list of endangered species of Brazilian fauna. A more in-depth study of Supply Chain Sustainable Management (SSCM), to structure a circular economy process, should identify and analyze more steps to detail an efficient flow of materials and information in the reverse supply chain. SSCM can help optimize the transport, storage, processing, and tracking of solid crab waste to minimize losses and maximize the use of by-products; it can develop performance indicators for the management of the reverse supply chain of crab waste. Metrics such as material recovery rates, energy efficiency, logistics costs, and stakeholder satisfaction can be used to assess performance and guide decision-making in the implementation of the circular economy. The SSCM area, in this context, can drive the adoption of advanced technologies, such as the traceability of links from the capture stage to the waste generation stage using blockchain, and automated recycling systems and remanufacturing processes, to improve the efficiency and quality of the by-products eventually derived from crabs [27].

(**a**) (**b**)

Figure 2. Artisanal crabbing process (**a**) and transport of live crabs in the Parnaíba Delta (**b**) (Ma-Brasil). Image used with permission from Editora IABS: Book: Industrialisation of the Parnaíba Delta crab. Brasília, Codevasf: IABS, 2012. 172 p. ill. color [8].

2.4. Systematic Literature Review Approach

2.4.1. Systematic Literature Review Approach

We conducted a systematic literature review to address the research questions of this study and test the established hypotheses. The review was performed using academic databases including Scopus, Web of Science, Portal Periódicos Capes (Brazil), and Google Scholar, as well as the Rayan, Parsifal, and Covidence applications [28]. The review protocol was structured based on the P.I.C.O. concept (Population, Intervention, Comparison, Outcome), following the guidelines outlined in the PRISMA statement [29]. Figure 3 illustrates the PRISMA flowchart outlining the review process.

2.4.2. Research Questions and Hypotheses

It has been observed that solid crab waste, due to the characteristics of its shell, can be used for composting and fertilizer in Brazil. It is also known that in other countries chitin and other important by-products are a form of circular economy. There is a strong global commitment to reusing solid aquatic waste. One example is Europe and its Blue Growth strategy (2021), which envisages the development of a series of economic sectors based on the ocean, such as fishing and aquaculture [30]. What is not known; however, is the current state of research in the country and around the world on the circular economy practices of this Guaiamum and Uçá crab waste. There are no specific studies on the subject in question. This study aims to provide evidence of the circular economy practices of waste from these crabs in Brazil. The main research questions guiding this review were as follows:

What is the current state of sustainable management of the reverse supply chain for Guaiamum and Uçá crab waste in Brazil, with a focus on the circular economy, considering governance and recent developments?

What evidence exists in the literature regarding the potential contribution of the circular economy of solid Guaiamum and Uçá crab waste, its applications, and sustainability in Brazil?

How can the adoption of circular economy practices contribute to the efficient management of solid waste from Guaiamum and Uçá crabs in Brazil, considering its socio-economic, environmental, and legal aspects?

Are there by-products or ways of reusing solid crab waste that could generate additional income for members of this production chain?

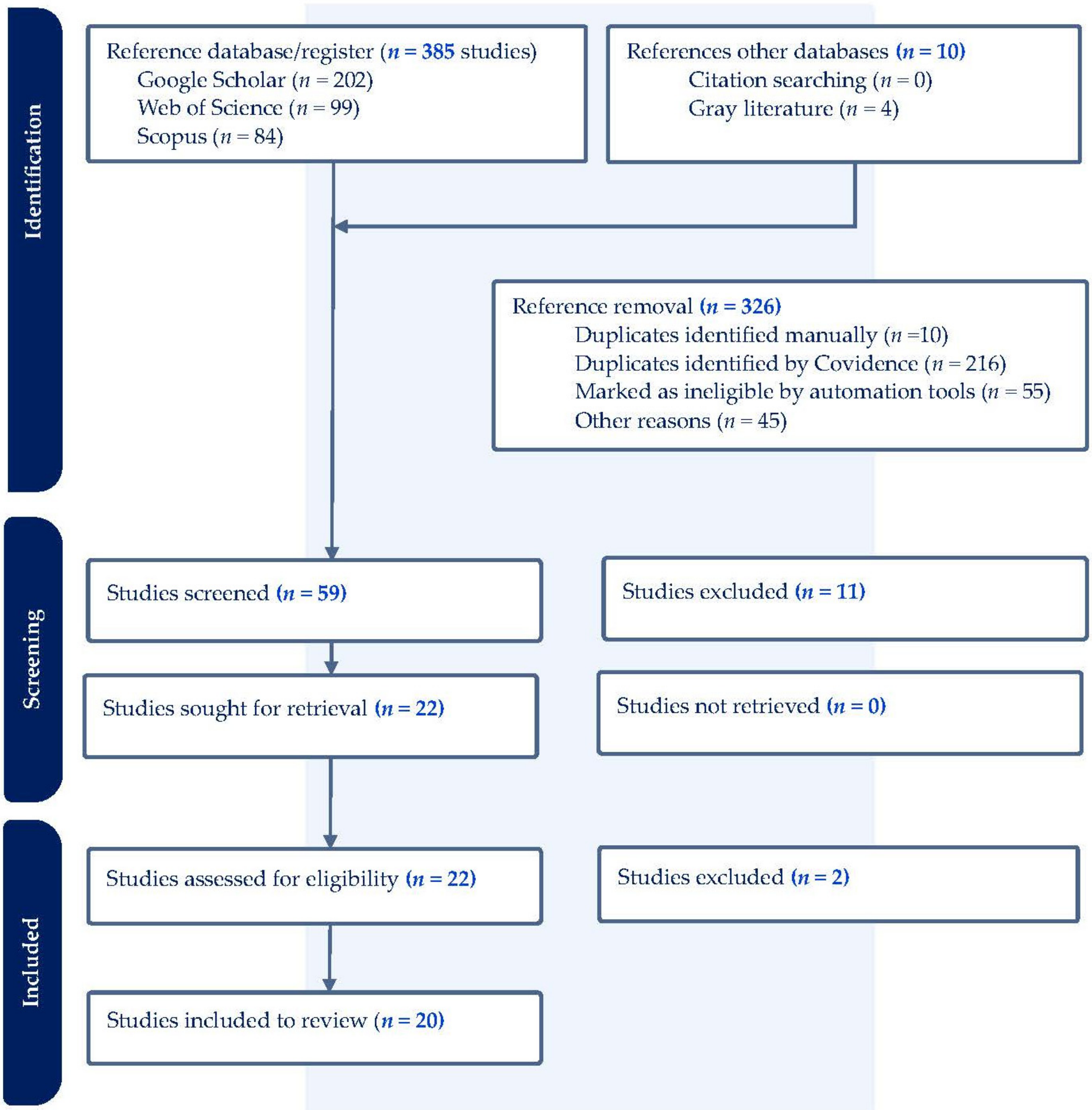

Figure 3. PRISMA flowchart showing the final results (adapted from [27,28]).

2.4.3. Eligibility Criteria and Search Strategy

We included articles, theses, and scientific papers published between 2014 and 2023 in Portuguese or English, focusing on the applications of by-products derived from Guaiamum and Uçá crabs in the context of the circular economy, and biological issues related to the species. The search terms were carefully selected based on their relevance to the research topic and combined using Boolean operators such as "AND" and "OR" to refine the search and obtain specific results.

2.4.4. Screening and Selection of Studies

The initial selection of articles involved screening titles and abstracts, followed by a full-text review of selected articles. Data extraction focused on information regarding the by-products derived from Guaiamum and Uçá crabs, their applications in the circular economy, and associated environmental and socio-economic impacts.

Despite the limitations inherent in our study, such as the specificity of the topic and the scarcity of the literature, we employed the PRISMA methodology to ensure a rigorous systematic review. While acknowledging gaps in current knowledge, particularly in the emerging field of circular economy in Brazil, our study provides valuable insights and highlights areas for future research.

3. Analysis and Discussion of Results

In this section, we discuss the findings of the systematic review of the use of crab residues and other relevant information obtained from the reviewed studies.

3.1. Use of By-Products from Solid Waste of Guaiamum and Uçá

Currently, the species in Brazil is consumed mainly for its meat on a large scale, especially in the coastal area. However, its by-products are not widely used. Studies carried out before the deadline of our research (2014–2023) point to the use of the residues as composting and fertilizer. However, the crab shell is already widely exploited in other countries through chitin derivatives, as shown in Table 1:

Table 1. Circular economy practices and use of crab waste by country.

Country	Current Practices	Circular Economy Practices	Differences/Challenges	Trends/Progress
Brazil	Disposal of unused waste	Reuse of by-products for animal production	Lack of awareness of the potential of the circular economy	Encouraging research and development of innovative solutions
India	Energy recovery	Recycling and biofuel production	Limited infrastructure for recycling	Investments in recycling and energy production infrastructure
USA	Utilization	Using waste to produce bioplastics	Economic incentives for the circular economy	Implementation of policies and financial incentives
China	Using waste efficiently	Chitin and fertilizer production from waste	Raising awareness of the benefits of the circular economy	Awareness-raising and education campaigns

3.2. The Situation of Crab Pickers

There are 800,000 artisanal fishermen in Brazil, and the lives of these crab pickers are directly affected by the waste management practices of the Guaiamum and Uçá crabs. Studies show that these people face difficult and subhuman conditions, being subjected to diseases and contamination during their work activity, and that the adoption of circular economy practices can improve their quality of life and generate additional income for these communities [6]. Studies on the socio-economic profile of crab pickers in the Parnaíba Delta indicate that the income obtained from this activity is less than the minimum wage [31]. A similar situation exists throughout the country. The adoption of circular economy practices in the use of crab waste can improve their quality of life and generate additional income for these communities. One of the most studied crab by-products is the shell (exoskeleton), which can be used to produce materials such as chitosan, bioplastics, and biofuels. Particularly, chitosan has been used as an antimicrobial coating in biopolymers for food packaging and food preservation applications. In Brazil, the studies, considering the period of our intervention (2014–2023), point to its use only as compost and fertilizer (see Table 2).

Table 2. Comparison of academic production of studies on the use of solid crab waste.

Activities	Brazil	Abroad
Flour	2	0
Composting	1	0
Extraction of Biocomposites	1	12
Other uses	0	10

3.3. Results of Systematic Review

Of the 385 studies that emerged from the search process, 102 duplicates were excluded, leaving 288 for evaluation. Of these, 229 were excluded for the following various reasons: before 2014, lack of framing, languages other than English and Portuguese, articles without full text, articles without open access, articles researching fish, shrimp, and mollusk species, articles on crab physiology or morphology, articles on crab capture techniques or habitat, crab diseases, etc. The PRISMA flowchart is presented in Figure 3 to illustrate this process.

After a thorough analysis of the entire text, 20 studies were included in the systematic review. The studies included in this review are summarized in Table 3, which presents the main characteristics of the studies (year, country, authors, population, intervention, exposure, outcome, and main results):

Table 3. Studies related by eligibility criteria—main characteristics of the included studies (year, country, authors, population, intervention, exposure, outcome, main results).

Refs.	Key Results
[32]	The use of mangrove crab flour in the agroecological cultivation of iceberg lettuce proved to be viable and promoted collaboration between an Extractive Reserve and a Popular School of Agroecology
[33]	The application of organic compost containing mangrove crab waste (5%) plus dried leaf cuttings with gliricidia in the cultivation of coriander at a dosage of 60 t ha^{-1} provides better agronomic characteristics. This alternative organic compost is an excellent source of calcium, helping to improve and correct more acidic soils.
[34]	The use of solid waste from the mangrove crab has proved to be an alternative source of income and sustainable use, contributing to the valorization of this waste.
[35]	The porous biomaterial prepared from crab shell waste showed efficiency in removing aqueous Cu(II) pollution, presenting the potential for environmental remediation applications.
[36]	Recycling crab shell waste into reinforced poly(lactic acid) biocomposites has proved to be a promising approach to producing sustainable materials for 3D printing.
[37]	The study highlighted that marine crab waste is a valuable source of chitosan and explored the optimization of chitin extraction to adjust the properties of chitosan.
[38]	Crab shells converted into calcium oxide (CaO) impregnated with zeolite type ZSM-5 (Na-ZSM-5) were used as a solid catalyst for the transesterification of neem oil (Melia azadirachta) into biodiesel. It is a cleaner fuel than gasoline and can help reduce greenhouse gas emissions. The production of biodiesel from crab shell waste is a way of promoting the circular economy.
[39]	The study investigated the thermal degradation of crab shell biomass as a nitrogen-containing carbon precursor, providing relevant information for its application in pyrolysis processes.
[40]	The study looked at the production of biogas from crab harvesting waste, highlighting its potential as a renewable energy source.
[41]	Although this article focuses on brake pads, it explores the use of crab shell waste in automotive products. This highlights the possibility of valorizing crab waste for industrial applications. Analysis of circular economy practices in automotive products can provide insights into the adoption of these approaches in other sectors.
[42]	Carbon materials derived from crab shells have shown promise for applications in high-performance supercapacitors, contributing to the recycling of waste.

Table 3. *Cont.*

Refs.	Key Results
[43]	Chitosan derived from blue crab waste showed suitable physicochemical, microstructural, and thermal characteristics, as well as bioactivity, indicating its potential use in various applications.
[44]	The development of bioprocesses has proved to be a sustainable platform for the production of alkaline phosphatase from crab shell waste, contributing to the environmentally friendly management of this waste.
[45]	The proposed processing method enabled the creation of durable and sustainable superhydrophobic coatings based on chitosan derived from crab shell waste, showing potential for various applications.
[46]	The use of a biodegradable electrolyte derived from crab shells has proved to be a sustainable approach to the development of high-performance and sustainable zinc batteries, a new type of battery made from crab shells. The battery is made with a new form of electrode made from a material called chitin, which is a natural polymer found in crab shells.
[47]	This article is about the blue bioeconomy in the circular economy through sensitive analytical research on crab waste. It highlights the relevance of preserving ultrastructure and nano-morphology in crab waste for the production of value-added by-products. This may be relevant to understanding how the transformation of crab waste into higher-value products aligns with the circular economy.
[48]	This study explores the addition of mangrove crab waste to precast concrete. There is a wide variety of precast artifacts that do not require high strength, such as tree guards, railings, and garden decoration (paths), among others, which can probably be produced with these levels of inclusion, in line with the circular economy.
[49]	It highlights the possibility of extracting chitin from crab waste. This could be relevant to understanding how crab by-products can be converted into valuable compounds, in line with the circular economy.
[50]	Blue crab waste can be converted into carbonaceous materials through pyrolysis. Carbonaceous materials can be used to create new products with industrial applications, such as water filters and purifiers, wear-resistant coatings, aircraft and vehicle components, medical devices, and even batteries and capacitors.
[51]	By-products from seafood processing can be used to produce functional compounds, biomaterials, biogas, and compost. Industry 4.0 can be applied to reduce and valorize marine waste, in line with the circular economy and the UN SDGs.

Notably, this analysis shows the interest in research on circular bioeconomy, as evidenced by the increasing number of studies on this topic, according to Table 3. The analysis of the selected studies reveals a growing interest in research on circular bioeconomy, highlighting the potential of crab waste for various applications, including energy transition, carbon footprint reduction, and climate change mitigation. In addition to the contributions of Rangel et al. [32] and Ramos and Ribeiro [33], who explored the use of Uçá crab flour in agroecological cultivation of iceberg lettuce and organic composting of crab residue in coriander cultivation, respectively. Other studies also offer valuable insights. For instance, Ribeiro and Fernandes [34] investigated Uçá crab solid waste management, highlighting its contribution to alternative income and sustainable use. Ge et al. [35] developed a porous material prepared from crab shell waste for effective removal of aqueous Cu(II) pollution, while Yang et al. [36] explored the recycling potential of crab shell waste into reinforced poly(lactic acid) biocomposites for 3D printing. Moreover, Gîjiu et al. [37] demonstrated that marine crab waste is a valuable source of chitosan, while Vijayalakshmi and Ranjitha [38] used crab shells for biodiesel production as a way to promote circular economy. Sebestyén et al. [39] investigated the thermal degradation of crab shell biomass, providing relevant information for its application in pyrolysis processes. Additionally, Dewantoro et al. [40] examined biogas production from crab harvesting waste, highlighting its potential as a renewable energy source. Singaravelu et al. [41] developed eco-friendly brake pads based on crab shell powder, emphasizing the possibility of valorizing crab waste for industrial applications. Fu et al. [42] studied carbonaceous materials derived from crab shells for high-performance supercapacitors, contributing to waste recycling. Metin et al. [43] characterized chitosan derived from blue crab waste physicochemically, highlighting its suitable characteristics for various applications. Abdelgalil and Abo-Zaid [44] developed a sustainable bioprocess for alkaline phosphatase production from crab shell waste, contributing to environmentally friendly waste management. Roy et al. [45] proposed a method for durable and sustainable superhydrophobic coatings based on chitosan derived from crab shell waste. Finally, Hu et al. [46] demonstrated in the laboratory the feasibility of a new type of battery made from crab shells, using an electrode made of chitin, a natural polymer found in these shells. These studies underscore the vast potential of crab waste to drive the transition to a more circular and sustainable economy. By effectively harnessing these resources, Brazil and other regions can not only reduce waste and pollution but also promote the development of new industries and mitigate the effects of climate change.

The analysis of these research works also provided insights and new conceptual relationships based on the hypotheses, research questions, and objectives of the study. Several relevant descriptors were identified in these studies, including sustainability, efficiency, reuse, recycling, circular supply chain, innovation, collaboration, compliance, life cycle analysis of the crab production chain, impact measurement, education, awareness, financing for investment projects, income generation for the community, volume of solid crab waste collected, and circularity of waste. The analysis of this set of data revealed, among these descriptors, which elements are most important for the adoption of circular economy practices in Brazil, according to the UN's Sustainable Development Goals [21]. The criteria were parameterized by assigning numerical values to each descriptor. The values were assigned according to their importance and priority for the circular economy. The descriptors that are most relevant to the adoption of circular economy principles, such as sustainability and waste reduction, were weighted more heavily. Descriptors that are more relevant to the SDGs, such as poverty reduction and the protection of ecosystems, were also weighted more heavily. Descriptors that are more relevant to the various applications of crab shell waste, such as upcycling, circular bioeconomy, and sustainability and eco-efficiency, were also weighted more heavily. However, weighting and parameterizing the criteria is a complex task. In the case of this study, parameterization was carried out based on a systematic literature review and an analysis of the principles for adopting the circular economy and the SDGs for potential application in the context of crab waste in Brazil.

Based on these elements, the study generated Figure 4 by parameterizing the data and weighting the criteria to group each descriptor according to importance and priority for the circular economy of solid Guaiamum and Uça waste in Brazil.

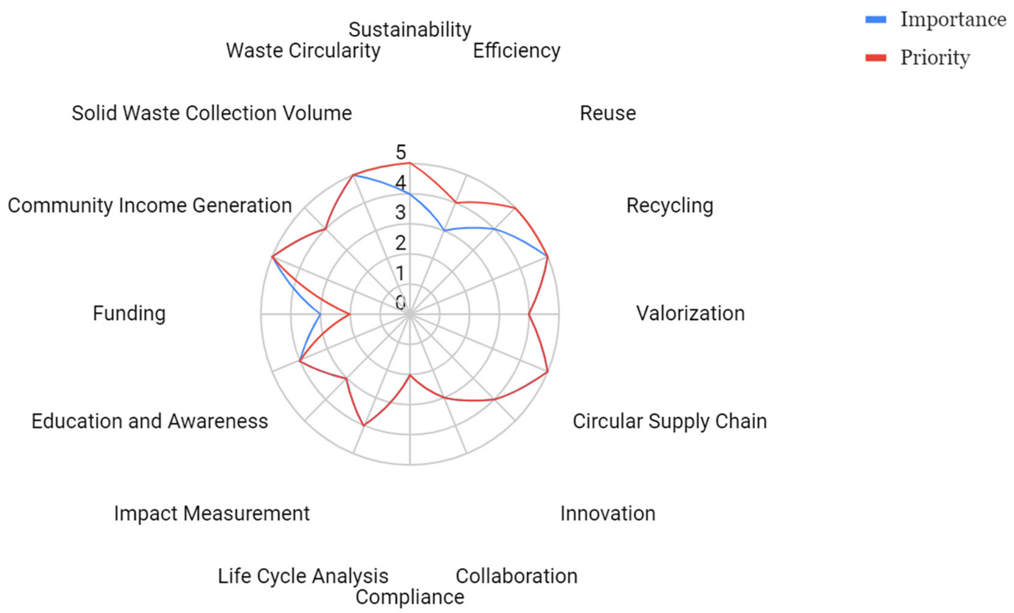

Figure 4. Importance and priority for the circular economy of solid Guaiamum and Uça waste in Brazil.

Based on the weights and relevance assigned to the descriptors mentioned, it can be seen that sustainability, reuse and recycling, the circular supply chain, and income generation for the community are considered the most important for the circular economy of solid Guiamum and Uça crab waste in Brazil. These descriptors have high relevance and weights, indicating their significant importance to the article's theme. Other descriptors, such as efficiency, innovation, and valorization, are also considered relevant, although with slightly lower weights. This suggests that these factors play an important role in the circular economy but are not as central as the descriptors mentioned above. Descriptors such as collaboration, compliance, financing, and impact measurement have lower relevance and weights compared to the other descriptors. This indicates that these factors play complementary roles in the circular economy but are not considered as crucial as the other descriptors.

These descriptors were grouped into conceptual thematic axes of circular economy, as shown in Table 4.

Table 4. Thematic grouping axes of solid waste circular economy descriptors from Guiamum and Uça.

Thematic Axis	Descriptors
Sustainability and Waste Management	Sustainability (SDG 12), Reuse and Recycling (SDG 12), Circular Supply Chain (SDG 12), Life Cycle Analysis (SDG 12), Volume of Solid Crab Waste Collected and Circularity of Waste (both SDG 12)
Efficiency and Innovation	Efficiency (SDG 9), Innovation (SDG 9)
Valorization and Income Generation	Valorization (SDG 8), Income Generation for the Community (SDG 1, SDG 8, SDG 12)
Collaboration and Compliance	Collaboration (SDG 17), Compliance (SDG 16)
Education and Impact Measurement	Education and Awareness (SDG 4, SDG 12), Impact Measurement (SDG 12)

4. Conclusions

The circular economy of solid waste from Guaiamum and Uçá in Brazil is an emerging and highly relevant field of study. The analysis of the selected articles and the conceptual descriptors provided a comprehensive view of the topic and highlighted the importance of the circular economy and its sustainable application in this specific context. From each type of study currently carried out, it was possible to identify the main drivers for the structuring of a supply chain based on the governance of the circular economy of solid waste from Guaiamum and Uçá in Brazil. The analysis of these results demonstrates the potential of the circular economy in transforming solid waste from Guaiamum and Uçá into valuable by-products, such as flour, composting, and extraction of bioactive compounds.

This systematic literature review study provided evidence of a large gap between the practices adopted in Brazil and other countries, especially regarding the use of solid crab waste. While studies in Brazil suggest that it is used to a greater extent in applications with lower added value, such as fertilizer, soil composting, and flour, in other regions of the world there is an advanced use of the circular bioeconomy, mainly exploring chitin biocomposites, although there are already studies based on the idea of transitioning the global energy matrix. This discrepancy reveals the urgent need for incentives and efficient structuring of the crab supply chain in Brazil. However, despite the existence of public policies for the management of the closed season of artisanal fishing, there is a clear lack of public policies for the governance of the production chain of Guaiamum and Uçá waste and specific strategies to promote the circular economy in this context in Brazil, i.e., there is no funding to structure a sustainable chain for processing, especially in the context of the circular bioeconomy of solid Guaiamum and Uçá waste, and there is also no legislation to promote better living conditions for the pickers. The lack of specific coordination in the reverse supply chain for solid Guaiamum and Uçá waste in Brazil could affect the implementation of the circular economy. It is important and necessary to overcome these potential challenges to make this circular economy of crab waste viable, such as the lack of adequate infrastructure for the collection, transportation, and processing of this waste, the lack of technical knowledge to transform this waste into new products, and the lack of financial and regulatory incentives to implement initiatives in this direction. The failure to comply with these development elements in this area represents a significant loss of economic and sustainable opportunities, since the applications of chitin biocomposites in sectors such as food, pharmaceutical, and cosmetics could add considerable value to the by-products of solid crab waste. It is also essential to raise awareness among the stakeholders involved and establish collaborative governance mechanisms that include all relevant actors.

This article contributes to the existing literature by providing a comprehensive and updated review of the circular economy of solid waste from Guaiamum and Uçá in Brazil, identifying the main gaps and challenges for its implementation. The article also has practical implications, as it can guide decision-makers and supply chain managers in the formulation and execution of policies and strategies that promote the circular economy in this context. In addition, the article can stimulate new research on the topic, exploring the opportunities and benefits of the circular bioeconomy of solid crab waste.

This study also highlights the urgent need for further research on the use of solid crab waste from Guaiamum and Uçá crabs, especially in the governance process for their reverse supply chains in the context of the circular economy. This approach provided it is integrated, combining scientific research, technological innovation, public policies, and strategic partnerships, will make it possible to exploit the full economic and sustainable potential of these by-products, promoting socio-economic and environmental benefits for the country and the communities involved, meeting the UN's Sustainable Development Goals.

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