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Review

Snail Shell Waste Threat to Sustainability and Circular Economy: Novel Application in Food Industries

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Abstract: Effective waste management has become an urgent societal challenge. Food waste is made up of items meant for human consumption that are lost, polluted, disposed of, or deteriorated; the reutilization of shells from mollusk waste is a severe problem in terms of environmental protection and the development of the circular economy. The properties of waste shells are presented and discussed, including their biological–natural origin and high calcium carbonate content. This could add social and innovation focus on shell waste management, getting a non-toxic, eco-sustainable, low-cost, biodegradable supplement to invest in. Furthermore, it has the potential to support the circular economy approach by creating a closed system that minimizes the use of natural resources and environmental contamination. This review explores edible mollusk shell waste sources and functional properties of inorganic components of snail shell waste like minerals and active substances like chitin, chitosan, and calcium carbonate and attempts to carry out a comprehensive analysis of the scientific literature published over the last 20 years, elucidating prominent patterns in the utilization of shell waste in food application industry, as additives and supplements development to promote both human and animal health.

Keywords: shell waste; food; ecology; circular economy; waste valorization

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1. Introduction

Effective waste management has emerged as a critical social issue, particularly with regard to waste reuse. Its utilization, especially in the case of biomass wastes [1] and challenging-to-handle waste, can advance cost-effectiveness and sustainability in the fields of food innovation and the green economy. More specifically, there is a need to research and develop agro-food waste treatment systems to minimize the impact on the environment [2]. One of the primary challenges is lowering the amount of waste produced by recycling and reusing it to create products with additional value to respect the circular economy and bioeconomy principles [3–5]. Using food waste as animal feed is a solution that addresses challenges related to food waste management and food safety but also reduces the need to develop conventional feeds, which is a resource and environmentally intensive effort [6]. Managing food waste is an achievable social, political, and environmental solution that promotes a circular economy. In the next years, there will be a significant rise in the need for food production due to the growing global population.

In these conditions, substantial amounts of food industry waste are gaining more and more attention from the scientific, political, and economical spheres. A third of the food produced for human use is lost or wasted worldwide, according to the Food and Agriculture Organization. Except for the retail and domestic phases of the global food supply chain, the FAO's most current data from 2019 shows that 13.8% of food produced in 2016 was lost from farm to table, highlighting the need for improved waste management systems considering the depletion of natural resources. According to national and international regulatory frameworks, minimizing waste release and maximizing its value (while maintaining standards for food and feed safety and quality) are essential tactics for an efficient management system to generate a real food industry's sustainability [7]. Reducing pollution and the quantity of scarce resources consumed are made possible by solid waste management, which also lowers costs and strengthens the green economy. Not only will the economy expand when this happens, but people will also live better, healthier lives.

Food waste can be processed using technologies like anaerobic digestion and composting to produce inputs for food production, such as organic fertilizer, and this strategy also promotes a circular economy [8]. The amount and extent of food waste and loss varies by organization, culture, and region. Using traditional food production and processing technologies, food waste also occurs at the beginning of the supply chain, including harvesting, storage, and packaging [9]. It is estimated that by 2025, food waste in Asia will expand from 2.78 billion tons to 4.16 billion tons. Especially in China, the periodic growth rate of food waste has been assessed to be more than 10 in recent times due to the acceleration of industrial growth and urbanization [10]. The main goal of the nation's scientists is to reintroduce food waste and extra fruits and vegetables into the food chain for use as animal feed [6]. Snail shells are an abundant, inexpensive, and natural waste. Snails are valued as a gastronomic food in several countries. They are an easily obtainable source of protein for local communities that dispose of their shells as waste [11]. The global market for snail goods and delicacies was anticipated to be worth USD 593.4 million in 2022. From 2023 to 2032, the market is expected to develop at a compound annual growth rate (CAGR) of around 10.33%. (Figure 1) [12]. In several Asian countries, including China, Hong Kong, Japan, Thailand, Taiwan, and Indonesia, the use of snail meat in their cuisine has become an alimentary habit, but [13,14] the amount of shell waste has caused huge environmental damage, both on land and in water [15,16]. This condition has a high potential in terms of economic benefits because shells are discarded after the meat is removed, but an enormous quantity is often left in landfills, polluting soil and air [17]. In nature, the hard nature of this component is related to its several important roles: it acts as protection against physical damage, predators, and desiccation [18].

Figure 1. Empty snail shells waste.

Freshwater and edible snails are frequently traded for their meat in certain countries. Numerous techniques could be used to recycle these wastes and transform them into beneficial calcium compounds in an environmentally responsible way, which is a suitable choice for zero-waste management.

In this review, we highlight the benefits of the chemical compound content of snail shells from the gastropod class for the increasing importance of the reuse of food waste in important health fields like human supplement and animal feed production for both health purposes and a bio-based economy developing with low economic value (Figure 2) [19]. All resources are lost when food is wasted, including the calories and nutrients it contains [20], with the goal of reusing food waste for feed production, an extensively studied area of research, both for health purposes and for the developing bio-based economy [6]. Calcium-containing substances such as snail shells are abundant throughout the world [21]. This review offers significant information on food manufacturing and shell waste, aiming to enhance comprehension of present food manufacturing operations and assess existing practices for managing food waste, thereby establishing a basis for the adoption of alternative solutions for valorizing food waste.

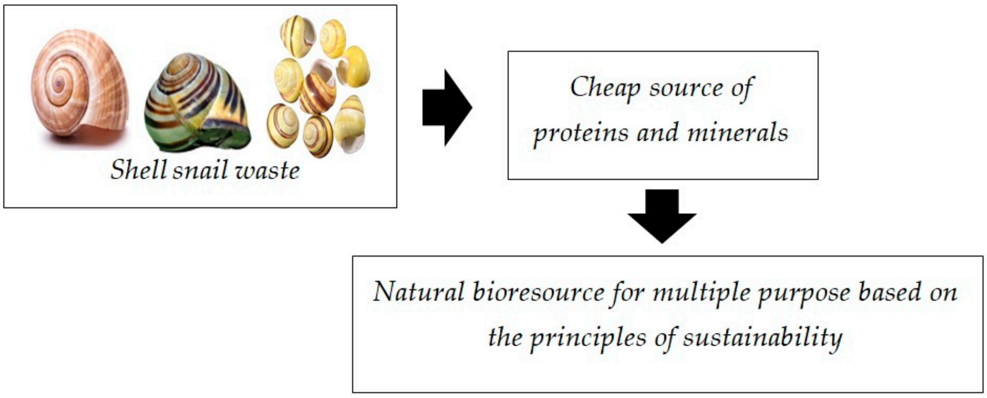

Figure 2. Benefits of shell content reuse.

2. Snail Shell Composition

In mollusks, shells are composed of more than 95% inorganic minerals such as phosphorus, manganese, iron, copper, zinc, sodium, potassium, and a tiny quantity of organic matrix [22,23]. In adults, calcium carbonate ($CaCO_3$) is typically found as calcite and aragonite; in juvenile animals, it is frequently found as amorphous calcium carbonate (ACC) [24,25]. Unlike the restricted forms of inorganic substances, there is much diversity in the organic matrix, which includes proteins, lipids, and polysaccharides involved in regulating shell formation; the regulation of $CaCO_3$ precipitation, encompassing nucleation, polymorph selection, and morphology modification via self-assembly and binding to the polysaccharide scaffold is largely dependent on shell proteins [22,26]. Active chemical substances found in snail shells include chitin $(C_8H_{13}NO_5)_n$, the primary organic material used to make chitosan. $(C_6H_{11}NO_4)_n$ [27]. The membrane-shaped tissue of the mantle is divided into compartments by mineralizing cells that line its exterior and secrete both inorganic constituents and organic matrix. Therefore, the characterization of freshwater snail shell wastes is a prerequisite for promoting their diverse uses as biological materials. These substances have potential applications as biomaterials in the medical field. However, the habitat, environment, mineral content, and microorganisms of snails all have an impact on the bioactive component profile of their shells [28].

2.1. Proximate Composition of Snail Shell

Foods' proximate composition is made up of their protein, carbohydrate, lipid, and moisture contents (Table 1). The inclusion of these food components can be of great significance to the food industry, as they present an analytical opportunity for product development and quality control, allowing for improved product formulations and more rigorous quality assurance processes (QC) or regulatory reasons. The analysis of proximate composition conducted by Jatto et al. (2010) [29] showed a higher level of carbohydrate value, calculated as nitrogen free extract (NFE), as a soluble carbohydrate. In *Achatina*

achatina species (African giant snail), it could lead to the use of these ingredients in the development of new 'healthy' products. The findings of a study carried out by Nkansah et al. (2021) [18] on three different snail species, such as *Achatina marginata*, *Achatina fulica*, and *Achatina achatina*, showed and confirmed that ash, which can range from 94.8% to 96.31%, is the primary component of the snail shell in *Achatina marginata*, indicating the quantity of carbon compounds and inorganic components. These findings are very interesting because what is often thrown away seems to be the major source of the nutrients sought when the flesh of these organisms is used as food, as a source of mineral supplements in drugs, cosmetics, food, food additives, animal feed, confectionaries, etc.

Table 1. The proximate and energy content (%).

	(%)							
Snail Species	**Protein**	**Fiber**	**Fat**	**Ash**	**Carbohydrate**	**NFE**	**Energy (KJ/100 g)**	**Ref.**
Achatina achatina	0.12	4.06	0.79	2.00	nd *	93.04	nd *	[29]
Achatina marginata	0.42	3.37	0.75	10.00	nd	85.46	nd	
Achatina fulica	0.30	3.96	0.38	10.00	nd	82.36	nd	
Limucolaria sp.	0.23	4.14	0.48	13.00	nd	82.15	nd	
Achatina marginata	2.1	0.5	0.68	96.31	0.64	nd	71.74	[18]
Achatina fulica	2.06	0.36	0.62	95.85	1.26	nd	79.38	
Achatina achatina	3.18	0.63	0.59	94.85	0.95	nd	92.04	

* nd = not determined; NFE = nitrogen free extract.

2.2. Chitin and Chitosan

Natural aminopolysaccharides, chitin, and chitosan polymers have distinct structures, multifaceted characteristics, extremely complex functions, and a variety of uses in the biomedical and other industries [30–32], particularly in the health sector, are useful as antibacterial agents. It is now highly sought after as a novel functional biomaterial with enormous promise across a range of industries, in addition to being an underutilized resource [33,34]. When analyzing the content of chitin and chitosan compounds in different snail shell species of the class Gastropoda, such as *Achatina achatina*, *Achatina fulica*, and *Archachatina marginata*, as reported by Sundalian et al., 2022 [28] and presented in Table 2, the highest content was found in *Achatina fulica* species by Maya et al., 2017 [35], more than the amount determined in other species often analyzed, which was about 67.16%.

Chitin compounds are converted into chitosan through a chemical process that includes demineralization, deproteinization, decolorization, and deacetylation (Figure 3) [27,36].

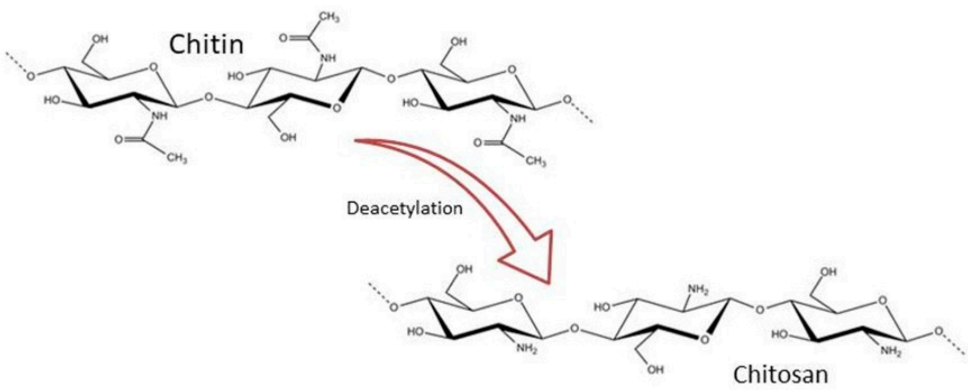

Figure 3. Conversion of chitin in chitosan polymer.

Table 2. Chitin and chitosan listed in percentage values in some *Achatina* species shells.

Species Name	Chitin (%)	Chitosan (%)
Achatina fulica	13.42	67.16 [35]
Achatina achatina	Unknown	46.37 [37]
Archachatina marginata	Unknown	35.85 [37]

The results of the chitosan test obtained from these shell species against potentially dangerous bacterial strains showed that an inhibitory power of 34.33 mm against Staphylococcus aureus was observed at an optimal concentration of 500 ppm [38]. Additional test results demonstrating a sensitive response were obtained from patients with diabetic ulcers caused by the *Staphylococcus aureus* bacteria at concentrations between 300 and 700 ppm [39]. *Achatina fulica* species-derived snail shell chitosan was tested for its positive antibacterial activity on cotton fabric by observing how different soaking times affected *Staphylococcus aureus* growth activity. According to this study, the longer the cotton cloth is submerged in chitosan acetate (*Achatina fulica*), the more effective it is at inhibiting bacterial activity [40]. The potential of chitin and chitosan to mitigate the usage of synthetic food preservatives lies in their antibacterial and antifungal attributes. Additionally, N-carboxymethylated chitosan, a water-soluble derivative, exhibits antifungal properties. In comparison to synthetic wraps, chitosan-based films surpass in terms of decreased oxygen permeability and improved moisture transfer. Furthermore, these films have demonstrated the ability to reduce browning in physically damaged fruits [41]. Currently, several businesses are engaged in the commercial production of chitin and chitosan products, with the majority of these businesses based in Japan, where over 100 billion tons of chitosan—roughly four trillion yen—are produced annually from the shells of crabs and shrimp, accounting for about 90% of the world's chitosan market [42]. The importance of chitosan extraction from food waste nowadays can be seen here. The presence of reactive functional groups can lead us to secondary byproducts production of quality in the food field because of their interactions with various food matrix components after integration into a new real product. Numerous investigations have demonstrated the efficacy of chitin, which has the potential to be used as a pharmaceutical additive and has antipathogenic and antioxidant qualities [29,43]. Moreover, it was discovered that chitin and its derivatives significantly modulate the immune system's response against cancer and exhibit antitumor activity by suppressing tumor angiogenesis factors, inducing apoptosis, and reducing cell adhesion [37]. Edible mollusk shells, specifically chitin and chitosan, manifest an extensive array of biological attributes encompassing antibacterial, antifungal, antiviral, antituberculosis, anticoagulant, antioxidant, anticancer, and anti-obesity properties [44–47].

2.3. Calcium Carbonate

As mentioned earlier, food waste is associated with nutrient losses. Chemical properties, together with the wide range of particle sizes, particle size distributions, and even different crystalline structures, make calcium carbonate an attractive starting material and the right carrier for various mixtures. Therefore, to increase the absorption of calcium from the diet, foods fortified with calcium are commercially available today [48]. Therefore, the calcium carbonate content of the snail shell needs to be extremely high in order for it to be considered a potential source for various industries, as Sundalian et al. (2022) have determined, finding that $CaCO_3$ is the major component of the shells (Table 3). In order to support the claim, Parveen et al. 2020 [49] attempted to clarify the physical and chemical characteristics of the shells of three Indian freshwater snails, namely, *Bellamya bengalensis* (Lamarck, 1882) (Gastropoda: Viviparidae), *Pila globosa* (Swainson, 1828) (Gastropoda: Ampullaridae), and *Brotia costula* (Rafinesque, 1833) (Gastropoda: Pachychalidae), for the assessment of the calcium carbonate content through field emission scanning electron microscopes (FE-SEM) and energy-dispersive spectroscopy (EDS) microstructure observation and characterization [50].

Table 3. $CaCO_3$ composition.

Snail Species	$CaCO_3$ Content (%)	Ref.
B. bengalensis	94.7	
P. globosa	95.8	[44]
B. costula	87.2	
Achatina achatina	98.5	[45]
Achatina fulica	48.11	[46]
Archacatina marginata	81.0	[47]
Limucolaria sp.	98.75	[45]

This increasing need to carry out the mineralogical properties characterisation analysis for snail shell powder in order to further elucidate its characteristic industry potentials also with energy dispersive X-ray (SEM/EDX), X-ray fluorescent (XRF) and the X-ray diffraction (XRD) analysis [51,52].

Images from scanning electron microscopy (SEM) and the corresponding energy dispersive X-ray spectroscopy (EDS) spectra of the shells confirm the high concentrations content (mean percentage of dry weight), supporting and somewhat validating the hypothesis that 95.0–99.9% of snail shells are made of calcium carbonate [53]. Strong calcium peaks, along with carbon and oxygen peaks and the incidence of magnesium and silicium peaks, are seen in the $CaCO_3$ polymorphs.

These chemical properties, together with the wide range of particle sizes, particle size distributions, and even different crystalline structures, make calcium carbonate an attractive starting material and the right carrier for various mixtures. Therefore, commercially available foods fortified with calcium are available to increase the amount of calcium absorbed from the diet today [54]. Calcium supplementation is often used to prevent and treat osteoporosis. Several calcium salts and formulations are available on the market worldwide. Many calcium supplements contain additional ingredients such as vitamin K and magnesium. The most commonly available forms of calcium are calcium carbonate and calcium citrate. Other forms of calcium include lactate, gluconate, and hydroxyapatite. Calcium supplements are available as capsules, tablets, powders, and liquids. Fortified foods can be produced from a great variety of sources, and shells are among the best sources of calcium for the heart, containing about 38% of it [55], which is frequently employed in the pharmaceutical industry, for instance, because it can neutralize stomach acid, so it is used as an antacid. There is a growing interest in animal agriculture to explore valuable alternative sources of nutrition, and snail shells, along with other food waste, are already being considered as a cheap alternative and sustainable solution to traditional high-cost sources of calcium. It has been. Calcium is an essential feed component in poultry diets, and its deficiency can lead to reduced shell quality and osteoporosis [56]. According to a study by Buwjoom et al. [57], feeding broiler chickens with snail shell powder improved their growth performance and bone strength. According to Yuvaraj et al. (2018) [58], there are antimicrobial benefits to combining $CaCO_3$ from Pomacea canaliculata with chitosan from Periplaneta americana. This means that the two compounds together can prevent the growth of bacteria such as *Escherichia coli*, *Pseudomonas aeruginosa*, *Bacillus subtilis*, and *Bacillus licheniformis*.

2.4. Other Mineral Elements

Minerals serve a multitude of purposes, including forming the components of our bones, impacting the function of muscles and nerves, and controlling the body's water balance [59]. Similar to vitamins and other vital nutrients found in food, different animal species have different mineral needs [60]. The two main categories of elements found in minerals are macro (major) and micro (trace). The ultra-trace elements fall into the third category. Calcium, phosphorus, sodium, and chloride are examples of macro minerals. Iron, copper, cobalt, potassium, magnesium, iodine, zinc, manganese, molybdenum, fluoride, chromium, selenium, and sulfur are examples of microelements [61]. The requirement for macrominerals is above 100 mg/dL, and the requirement for microminerals is below 100 mg/dL [62]. The ultra-trace elements, which have been identified in animals and are thought to be vital for these creatures, include boron, silicon, arsenic, and nickel. It is impossible to overstate the significance of mineral elements for plant, animal, and human nutrition.

As nutraceuticals, they have also acquired immense importance in recent animal science in that the nutritional and health-promoting effects of their constituents are considered to have beneficial pharmacological effects, contributing, for example, to the establishment of a normal physiological state of health, to the prevention of diseases and, consequently, to the improvement of production performance, and, as dietary supplements, they can reduce the use of antibiotics [63]. As reported in Table 4, in the study by Nkansah et al. (2021) [18], after calcium, magnesium was the second most prevalent mineral in all species' shell samples, Achatina fulica had the highest Na content in the shell samples studied (21.83 mg/100 g), and the only part of A. achatina that had detectable Zn was its shell (0.3 mg/100 g). As we know, Ca is an essential mineral element for human and animal health. It is necessary to sustain the best possible bone formation in childhood and during human development, whereas Mn, Zn, and Fe are regarded as necessary minerals for growth, disease prevention, and fundamental cellular functions [64]. While Mn, Zn, and Fe are thought to be essential minerals for disease prevention, growth, and basic cellular activities, the importance of Ca dependence in animal husbandry is already well established. It has been demonstrated that feeding Ca in the form of oyster shells is more effective than feeding the same amount of finely ground limestone because the larger particles dissolve slowly, resulting in higher Ca intake [64]. These results confirm the potential of snail shells as a source of mineral elements to supplement human diets and as feed for livestock, thus a green approach to waste utilization [18]. The analysis of mineral composition in the research of Jatto et al. (2010) [29] in some Achatina species showed that the shells of all species are composed of manganese, zinc, and copper but mainly contain iron. In particular, the shell of Achatina achatina species has the highest amount of iron; the value is 0.25123 mg/g.

The chemical composition of giant African land snail shells, Archachatina marginata, collected from six southwestern States of Nigeria, was studied by Akinnusi et al. (2018) [65]. Eighteen locations throughout the states were used to gather snails, with three locations in each state. The concentrations of magnesium, calcium, iron, sodium, potassium, chloride, and phosphorus were measured in the shells, evidencing calcium as the most abundant mineral element (1618.89 mg/100 g) and chloride was the least abundant (6.37 mg/100 g). Shells from Lagos State had the lowest concentration (745.6 mg/100 g), while those from Ondo State had the highest total mineral concentration (780.0 mg/100 g), with no discernible difference between them and those from Ekiti State. The table displays the overall mean value of the chemical composition of the snail shells from the six southwestern States of Nigeria. All the mineral elements studied were found in the shells but in different concentrations. Calcium was the highest (260.75–279.68 mg/100 g). The phosphorus content in the shells varies between 196.27 mg/100 g and 206.08 mg/100 g. The shells analyzed collected from Ekiti State had the highest concentrations of Mg^{2+}, Fe^{2+}, and K^{+} (although not significantly different from those from Ondo State), while the highest Ca^{2+} levels were found in the shells from Ondo State. Those from Lagos State had the lowest concentrations of Mg^{2+}, Fe^{2+}, and K^{+}. In another work by Dickson et al. 2013 [66], mineral content was quantified in three different samples carefully selected from different locations in Nigeria to cover the states of the Niger Delta region and to ensure geographic distribution/prevalence of animals (i.e., the locations where these animals are usually available and consumed in large quantities). From the results analyzed in samples of *Cochlicella acuta* (small snail), *Achatina achatina* (African giant snail), and *Thais callifera* (marine snail) species, the levels of calcium and sodium in the shells were far higher than those of other metals. The levels of metals for each species of animal were in the order Ca > Na > S > K > Mg > P > Fe > Zn > Cu > Se > Pb > Cu > Ni > Cr > Mn > Co for *Cochlicella acuta*; Ca > Na> Mg > Se > Pb > Fe >

Zn > Cu > Ni > Cr > Mn > Co > S = P for *Achatina achatina*; and Ca > Na> S > K > Mg > Se > Fe > Pb > Zn > Cu > Ni > Cr > Mn > Co > P for *Thais callifera*. The highest concentration of Na (1.300 mg/100 g), Mn (208.8 mg/100 g), Ni (800 mg/100 g), Pb (1.833 mg/100 g), Co (50 mg/100 g), and Se (5.000 mg/100 g) was found in *Achatina achatina*. The highest amount of Mg (30.633 mg/100 g), K (119.36 mg/100 g), P (21.08 mg/100 g), and Fe (8.645 mg/100 g) was found in *Cochlicella acuta* while the highest amount of Ca (220.00 mg/100 g) was found in *Thais callifera*. The levels of mineral elements present in the test shells provide us with important data from which to start so that the shells, otherwise discarded as waste, can enter with greater force into a recycling circle and be used as a source of mineral supplements; in particular, the high calcium content could be important for the formulation of feed supplements for farm animals, in particular laying hens [67]. In view of this, the shells of these organisms could then be processed, ground into powder, and used as food additives while meeting an increasing demand for the creation of a low-impact circular economy.

Table 4. Mineral content of different snail shell species.

Shell Mineral Content	mg/100 g																Ref.
	Ca	Na	K	S	Mn	Mg	P	Zn	Fe	Se	Pb	Ni	Cr	Co	Cu	Cl	
Cochlicella acuta	192.500	800	119.36	149.420	156.6	30.633	21.08	7.52	8.645	2.000	1.668	533.3	300	50	1.200		[66]
Achatina achatina	207.500	1.300	793.60	0.00	208.8	18.283	0.00	15.571	1.677	5.000	1.833	800	300	50	960		
Thais callifera	220.00	2.300	87.360	104.060	191.4	22.800	0.00	13.429	2.548	3.000	1.750	666.7	200	25	1.040		
Archachatina marginata (mean)	269.80	25.76	125.36			139.13	170.71		2.27							1.06	[65]
Achatina achatina					0.431			0.0985	25.123						0.647		[29]
Archacatina marginata					0.671			0.25	5.745						0.533		
Achatina fulica					1698			0.802	3.704						0.551		
Limucolaria sp.					0.199			6.3	20.858						0.446		
Archacatina marginata	13,716.09	5.92	24.95		0.33	50.09	BDL *	BDL	1.37						BDL		[18]
Achatina achatina	14,188.53	6.82	22.32		0.14	65.06	BDL	BDL	2.34						BDL		
Achatina fulica	14,375	21.83	26.41		BDL	119.71	BDL	BDL	3.8						BDL		

* BDL = below detection limit.

3. Materials and Methods

The increasing possibility of accessing bibliometric data sources offers great opportunities for the development of broad academic knowledge and research experience in all scientific fields, including the field of shellfish waste utilization. In this review, publication data from 1990 to date were retrieved from Google Scholar, Science Direct, Google Scholar, Elsevier, and Pubmed PMC, including research articles, books, and reviews, with a high percentage of results published before 2010; for this reason, our study focused on all the literature up to the most recent discoveries. The exponential increase in the number of scientific publications is remarkable. The value for the three-year period 2020–2022 suffers from the fact that only the months of January and February were considered for 2022.

The semi-systematic narrative review approach was chosen to conduct the literature review because it is a useful tool for providing an overview of common themes and presenting the state of knowledge in a particular area of research and its theoretical perspectives; it can also examine how research has gradually changed and developed over time. Applying this approach to analyze the evolution of the literature published since 2000, it became clear that the older and well-established applications were concentrated in the fields of agriculture, construction, and bioremediation, accounting for about 90% of the total literature. The reuse of shellfish in agriculture as a soil conditioner was the most frequently studied topic, accounting for more than 50% of the total literature. In addition, it was found that about 70% of the articles on traditional applications of reuse were published before 2015, with a significant decrease in recent years due to the maturity of these sectors, which probably require less contribution from cutting-edge research. In contrast, the use of shell waste as heterogeneous catalysts in biodiesel production has steadily increased; therefore, as expected, new applications in cosmetics and biomedicine have grown exponentially.

4. Food Industry Applications

Communities are trying to help solve the problem of sustainable use of existing shell waste, and many projects are being launched around the world to sensitize local people to its reuse as useful items. However, these practices are just a drop in the ocean until the valorization of shells and the development of new products become the main focus of the actual food industry [68]. The content of snail shells found in nature varies depending on the diet, including the influence of protein, microorganisms, and mineral content of the living environment, along with constant research about the active chemical compound content of several gastropod-class snail shells, which can be used as a reference basis for biomaterials, food industry preparations, animal feed, and pharmaceutical supplement preparations, this brief review aims to recognize the great potential of the use of snail shell waste and promote it.

The food industry generates substantial effluents during processing, which need to be treated/adsorped before being eliminated from the environment. Chitin and chitosan have gained attention for their adsorption properties and low cost. Furthermore, the presence of amino and hydroxyl groups significantly absorbs the toxic effluents. Their unique chemical structure (β-chitin), stability, chelation behavior, high reactivity, and selectivity toward contaminants make them excellent for adsorption [69,70]. Recent studies have investigated mollusk-derived β-chitin and chitosan as adsorbents for wastewater pollutants [71–73]. For example, chitosan from cephalopod waste was found to be effective in removing cadmium (Cd) from aqueous solutions under optimal conditions of pH 7, 42.5 °C, 220 min, and adsorbent dosage of 1 g/L [71]. This is the role of surface pores in adsorption. Nuggi et al. (2022) [72] showed that β-chitin in squid bones can significantly reduce turbidity, BOD, and COD in food processing wastewater.

4.1. Functional By-Product Production

Traditional Chinese medicine (TCM) is an ancient and important ethnomedical document that still holds an important place in healthcare in China and is also embraced by the Chinese population worldwide [74]. Mollusks are an essential component of many TCM recipes that are used to treat various medical conditions, where shells are either consumed whole or ground into a powder or decocted (heated to extract essence). A number of conventional respiratory medications with Indian origins contain the ashes of burned mollusk shells or cuttlefish bones that have been processed into pills, pastes, and solutions [75]. Traditional Eastern Mediterranean healers used to treat skin conditions, rheumatism, and stomach ulcers by inhaling smoke from opercula from the Muricidae and Strombidae families [76,77]. A particular incentive for research into anti-inflammatory compounds stems from the fact that mollusks are used extensively in traditional medicine to treat symptoms of inflammation and that mollusks are the most important mollusk product used worldwide for the same purpose [77]. However, many European civilizations believed that burning opercula ash could heal split veins [78]. Shells from *Monetaria moneta* have been used in India to treat a variety of conditions, including asthma [79], and in Zimbabwe, snail shells have long been used as a treatment for topical abscesses [80]. Overall, TCM therapeutic formulations benefit from the contributions of four classes of mollusks: Poly-placophora, Cephalopoda, Bivalvia, and Gastropoda, which have 2, 3, 31, and 34 species, respectively [81]. Immanuel G. (2012) [82] has investigated shell extracts with relevance to respiratory disease, demonstrating that powdered cowry (*Monetaria moneta*) shell can be used as an alternative medicine, and it has antipyretic, wound healing as well as antimicrobial properties.

A recent investigation by Chitprasert et al. (2023) [83] put an eye on the benefits of the use of $CaCO_3$-like nanoparticles to encapsulate and promote the gastrointestinal digestion and bioactivity of vitexin in vitro to improve the bioaccessibility for functional food application. Calcium carbonate is the most common and cheapest form of calcium. For many patients, cost plays an important role. A study that evaluated the cost of calcium from foods and supplements found that calcium carbonate was the cheapest form of calcium, accounting for about a third of the cost of the cheapest food sources, such as frozen skim milk and calcium-fortified orange juice [84].

This investigation revealed that the bioaccessibility, in vitro, was significantly enhanced by this nanoencapsulation with $CaCO_3$, guaranteeing higher antioxidant activity compared to the free vitexin. As a result, this study demonstrates that vaterite $CaCO_3$ nanoparticles are intriguing delivery systems for vitexin meant for use in functional food applications. Furthermore, the $CaCO_3$ nanoparticles are promising options for large-scale production and may raise the possibility of successful commercialization because of their established benefits and low cost [83].

Filter aids or clarifiers are currently used in industrial beer production to improve the quality and clarity of beer. These active ingredients help capture contaminants and/or suspended solids that form blockages or deposits [85]. Due to the high demand for these commercials, these raw materials are relatively expensive and not readily available; cost-effective and locally available alternative filter aids are needed. This can be achieved by finding alternatives to these commercial filter aids from some locally available sources, such as snail shell powder, which mainly consists of calcium compounds, specifically $CaCO_3$, as opposed to diatomaceous earth, which mainly contains silica from the remains of diatoms. Therefore, the use of some of these locally available products as filter aids during brewing has the potential to yield products with desirable qualities comparable to those achieved using commercially available filter aids. This study demonstrated that snail shell powder showed a moderate clarifying effect during the beer-making process, even though the clarity of beer treated with eggshells and other filter aids was excellent [86]. Nevertheless, improving the production of snail shell powder by improving its methods and cost could enhance its use as a potential filter aid in beverage clarification, especially for the large quantities of single-use snail shell waste that are practically available.

4.2. Valorization in Livestock Feed Supplement

Crushed shells are an important calcium supplement ($CaCO_3$) when included in livestock feed. Calcium supplementation is used to improve livestock health, especially bone health, as well as in laying hens as a supplement to improve eggshell quality and strength [87]. Replacing calcium in limestone with calcium in some marine shellfish increases bone development, egg production, and egg strength, weight, and thickness in chickens [88–91] and ducks [92]. It has been shown that, according to EU Regulation (EC) No. 1069/2009, shell waste can only be used as a feed additive if it does not contain meat in order to exempt it from classification as an animal by-product [93]. The allocation of standards is regulated by the respective authorities of each member state. Ultimately, the recovery of this species needs to consider the distance between shellfish production and farms, both from the perspective of environmental and economic sustainability [94]. Guan et al. In 2019, [95] reported that the use of chitosan and its derivatives (COS) has positive effects such as antioxidant, immunomodulatory, and antibacterial effects, and studies in various animals showed that COS has been shown to be a type of prebiotic used in animal nutrition. In this study, Rusdi et al. 2021 [96] investigated the effectiveness of including COS produced from the snail field *Pila ampullacea* in the diet on quail performance and carcass characteristics. The results of this study showed that the inclusion of chitosan oligosaccharides (COS) in the feed improved feed efficiency and improved the performance of quail.

5. Future Sustainable Perspectives and Conclusive Remarks

Not surprisingly, food waste is one of the target areas of the European Commission's Circular Economy Action Plan 2015, which aims to create sustainable jobs, growth, and investment and to reduce carbon neutrality, zero waste, and resources. It was updated in 2020 to help build a more efficient business and efficient economy [97].

The post-pandemic economic crisis has had a major impact on the global economy. As a solution, several suggestions and recommendations have been made by experts in several fields to deal with the economic crisis. The blue economy concept has been adopted by several countries to promote the economy while achieving sustainable exploitation of waste resources. Therefore, turning problems into potential benefits is the key discussed in the blue economy concept. From this perspective, the utilization of snail shell waste could be a potential solution to overcome such problems while promoting economics through the development of bioactive compounds. The result of these studies have given some insight into the mineral potentials of these shells; a comparison of the levels of the mineral element of the shells used in this studies to that of recommended daily dietary intake for mature humans, infants and animal feeds by the Food and Nutrition Board (FNB) of the United States (2004) [98] and the United States Food and Drug Administration (FDA, 2005), shows that levels of these parameters in the shells of these animals are high enough to satisfy the daily intake of man and other animals. Food wastes come from many different sources. Dairy processing wastes include whey, curd, and milk sludge from the separation process. Food wastes derived from processing vegetables include peelings, stems, seeds, shells, and bran [99]. These food industry wastes have poor biological stability, high nutritional value, high concentration of organic compounds, high water activity, poor oxidative stability, and optimal enzymatic activity, making their environmental disposal detrimental to the ecosystem [2]. The substantial quantity of food waste and the microbial breakdown of it can be detrimental to the environment and human health, causing high waste treatment costs that place additional burdens on food producers. Effective waste management is essential to the expansion of the food industry [100].

Spiral economy, a neologism coined by the president of the International Institute of Heliculture, develops "spirally" and includes various sectors: Haute cuisine with meat, medical and cosmetic products with mucilage, feeding other animals with intestines, and orthodontic products with calcium-rich shell. The growth potential of the sector is very high: according to the International Institute of Heliculture, the 1200 hectares currently cultivated in Italy meet only 15% of domestic demand, although demand for food and cosmetics has increased by 35% compared to 2019. A total of 85% of the product comes from abroad—Romania, Turkey, and Indonesia—but where the production is of poor quality, coming from long supply chains and not subject to the necessary health controls [101]. Again, according to the institute's estimates, in Italy, there is room for more than 3800 hectares of plants to cover the production gap.

In order to maximize the utilization of snail shells in fields like medicine, livestock feed, and agricultural production, sustainable management practices are needed [65]. For the ultimate purpose of using the shell by-product, a deeper comprehension of the snail's marketing chain is also necessary. For example, reports from markets in South Africa have shown that a large quantity of empty, calcium-rich snail shells are produced and discarded without disposal, while shells can be utilized as fertilizer to manage soil acidity and as feed for animals; powdered snail shell is already used in different kinds of as a source of calcium [102]. A wide range of chemical compounds can be found in the shells of land snails belonging to the class Gastropoda. It can be concluded from the findings of multiple studies on snail shells that the three most significant chemical compounds found in them are $CaCO_3$, chitin, and chitosan. In addition, other trace elements include the minerals potassium, sodium, zinc, iron, copper, phosphorus, and manganese, as well as a small number of other components such as dietary fiber, protein, little fat, and a high percentage of ash, are present. These substances have potential applications as biomaterials in the food and medical industries. The results of these studies show that the concentration of the mineral elements studied in the shells of these animals is higher than the values reported for the fleshy parts, indicating that the shells of these animals, otherwise treated as waste, are important as a source of most of these minerals for animal and plant nutrition. Calcium supplements are mostly found in the carbonate and citrate forms and are commonly used in fertilizers, as large doses of calcium supplements have been shown to improve bone health in children, adolescents, and postmenopausal women. It may be used in livestock and food industries. This review aims to provide new insights and guidelines for future research on nutritional supplements and animal feed from waste shells based on scientific evidence.

Therefore, after processing the meat parts of these creatures into food, it is highly recommended to collect the shells and store them in a clean container. Shell waste is an abundant and cheap renewable natural resource, but several obstacles must be overcome, or at least demonstrated, before large-scale use for comprehensive sustainability analysis. The skin can be recycled due to its high $CaCO_3$ content, but if it is to be disposed of after food production or consumption, organic residues and other impurities must be removed by high-temperature calcination followed by grinding to achieve 90–95% $CaCO_3$ purity. It must be removed through a screening process. This may be achieved depending on the end use [103]. Furthermore, in the context of a circular economy, the potential impact of shell waste collection and management systems should not be ignored in the overall sustainability analysis.

Individuals, organizations, and cooperating agencies should engage in the processing of these animal shells into food supplements, animal feed, and plant nutrients. Such ventures would lead to the emergence of artisanal businesses, increase the farming of shellfish, reduce unemployment, and create wealth from materials previously considered waste. Future studies need to tackle a number of important problems. To provide more accurate information on the full nutrient profile of food waste before treatment and, more importantly, of feed after treatment in terms of concentration, variability, and bioavailability of key nutrients, systematic sampling, and thorough nutrient analysis are required in the field of animal feed.

This information is essential for modern animal production systems to incorporate feeds made from food waste into their precision feeding regimen. The utilization of food waste not only reduces the inconvenience of waste dumping but also contributes to the more economical production of foods with nutritional and medicinal value, thus meeting the long-standing global demand to make nutrients and nutraceuticals available at low cost. Effective use of food industry byproducts can lower negative costs, lessen pollution, and show the food industry's sustainability, directly impacting the nation's economy. The food industry contributes to a waste-free society and country.

Based on a shell upgrade life cycle assessment (LCA) performed by Iribarren et al. [103], CO_2 eq. emissions for processing 100 tons of mussels to $CaCO_3$ are estimated at 0.775 tons, which is surprisingly higher than the landfill disposal scenario (in the above article, 0.496 tons of CO_2 per ton of mussel shells) (quantified as an equivalent amount). Although the landfill option appears to have a more positive impact, this option is the worst option from a sustainability and recovery point of view of valuable waste and is therefore completely discouraged. Then, de Alvarenga et al. [94] and Lee et al. [104] demonstrated significant environmental benefits associated with $CaCO_3$ capture, resulting in impacts of approximately 40% or less compared to landfilling or incineration as unsorted waste.

The evaluation of this snail shell waste is also very important for the aquaculture industry, public health, and the environment. Karthik et al. (2016) [105] tested Mw-sulfated chitosan obtained from *S. pharaonis* and obtained cytostatic activity, followed by anticoagulant and antiviral activities. Similarly, extracted β-chitin exhibited wound-healing properties against skin damage in rat models [106]. It is possible to obtain better functionality of chitin through the use of electrospinning or nanoparticles, methods that improve chitin action on the target site. For this reason, efforts should be made worldwide to recycle shell waste and turn it into real economic products. Finally, the aspects described above must be seen in the current historical context, where climate change is manifesting itself as one of the main problems facing humanity; through the food chain, technology can improve production sustainability and the use of waste as feed to meet social, personal, and nutritional needs [107].

There is a real chance for interdisciplinary researchers and industry to collaborate to make mollusk waste a bigger part of the circular economy paradigm through shell reuse and recycling.

The reduction of food waste and loss will remain a prominent focus of research in the upcoming years, with the expectation that this report could facilitate the advancement of sustainable food waste management and enhance the field of food technologies to attain a more comprehensive, integrated, and unifying approach and optimize human, animal, and ecosystem health, offering recommendations to fortify the implementation of the recent healthcare model "One health vision" [108].

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