Review

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Valorization of Proteinaceous Animal Waste to Amino Acids Reduces Environmental Pollution While Catalyzing Plant Functions in Sustainable Agriculture

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Valorization of Proteinaceous Animal Waste to Amino Acids Reduces Environmental Pollution while Catalyzing Plant Functions in Sustainable Agriculture

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Abstract: Global wastes accumulate at an accelerating rate especially food and slaughterhouse waste constituting a major proportion owing to inefficient management. The high protein concentration of fish waste and keratinaceous byproducts is hazardous, harbouring pathogens, and emitting toxins. Transforming proteinaceous waste into amino acids (AAs) reduces waste bulk and offers a smarter nutrient approach for agriculture. However, this resource remains underutilized triggering eco-system pollution, diseases spreading, and climate change. Currently, small quantities of proteinaceous waste are valorized as animal feed, fertilizer, and in medical, and biotechnological sectors, which cannot solve bulk waste accumulation further, natural AA sources in agriculture are less recognized meanwhile researchers focus on synthetic AAs. Introducing various plant-nutrient formulas enriching fish AA with keratinaceous waste hydrolysate has not been broadly discussed. With this novel approach, using proteinaceous waste resources in agriculture would solve environmental pollution while minimizing land degradation by synthetic fertilizer. In this review, we illustrate the potential and benefits of valorizing proteinaceous waste in bulk through bioconversion. More importantly, we spotlight the biocompatibility of natural AAs and propose an enrichment, to use the ultimate product as catalysts for crops. Consequently, this approach reduces hazardous waste while paving a paradigm change in agriculture.

Keywords: amino acids; fish processing waste; sustainable agriculture; waste management; waste valorization

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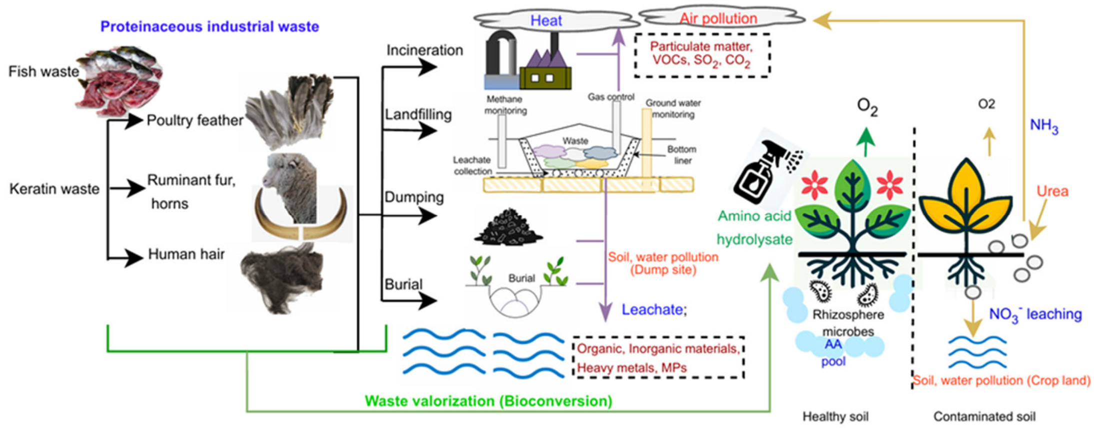
Graphical Abstract



1. Introduction

Rapid globalization generates a massive quantity of waste from every sector and their inappropriate management creates environmental menace. Industrial and municipal solid waste [1] mainly account for 7.6 billion tons, and 2.01 billion tons respectively, and agricultural wastes are composed of food and greens; 2.5 billion tons, and animal and livestock; 17 billion tons. When considering the components of waste, food and greens constitute the highest proportion, contributing 44 percent to the global waste stream [2].

Food and greens, animal, and livestock production expand owing to higher demand and technological advancements, thus accumulation of bulky waste is unavoidable. Fish Processing Wastes (FPW) generated in various stages of production contributed to 50–125 million tons in the world in 2018 [3] with 3.3 percent annual growth rate reported from 1950-2018 [4]. FPWs are mainly nonedible, nutrient-rich discards such as heads, viscera, bones, skins and fins, scales, and other fish trimmings [5]. Moreover, keratinaceous wastes [6] are generated exceeding 40 million tons annually which include human hair from personal care industries [7,8] avian feathers from poultry [9], animal fur from textiles [10] bovine hoof and horns from livestock industry [11].

To date, these proteinaceous wastes are managed to some extent through disposal or valorization however not sufficient to fully address the issue of high waste accumulation. FPW is used for advanced high-tech uses in biotechnological and engineering sectors, for the animal, aquaculture feed industry, and plant nutrient or fertilizer productions [12]. However, a major portion is sea or open land dumped or landfilled. Keratinaceous wastes, e.g., human hair are utilized for cosmetics, pest control, and hair care products, however, poultry feathers and animal wool byproducts, horns, and hooves are not valorized to a considerable extent. These are ultimately either open-dumped, landfilled with other municipal wastes, or incinerated [13] in bulk amounts aiming at waste disposal or power generation.

There are many adverse effects of the accumulation and unsafe disposal of proteinaceous wastes. Open dumping and incineration emit heat and other greenhouse gases (GHG), Volatile organic compounds (VOC), and particulate matter causing global warming and public chaos through health issues and foul odours due to the decomposition of protein. Open-dump leachate from human hair and animal keratin mixed with unsegregated municipal solid wastes increases nitrogen concentration in waterbodies causing eutrophication [8]. The spread of disease pathogens with protein decomposition such as Salmonella, E-coli, and further disease carriers such as rodents, mosquitoes, birds, and flies create a local nuisance [14]. Choking the drainage systems with the bulky waste clogging and emission of toxic gases such as ammonia, carbonyl sulphides, hydrogen sulphides, sulphur dioxide, phenols, nitriles, pyrroles, and pyridines with burning and posing respiratory disorders such as tuberculosis from dust hair and fur are further negative impacts [8].

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Therefore, a better solution for managing waste is of pinnacle importance. When considering these wastes at the monomer level, the common feature of all these industrial wastes is the availability of plant-biocompatible amino acids in optimum qualities and quantities. This composition is potent to foster plants supplying all 9 plants' essential amino acids (EAA) directly, other macro and micronutrients alongside other benefits of organic fertilizers [9] and conditions the rhizosphere assisting soil micro and macrofauna. Therefore, the best method for effective disposal is valorization to hydrolysate which appears with many secondary benefits. In this study, we propose a novel Fortified Amino Acid Fertilizer (FAAF) that can meet the full nutritional demand of crops with a potential substitute for Urea which exhibits detrimental effects on the environment in production and application.

In this review, we propose the most promising approach to managing proteinaceous waste with minimal ecological impact that may support attaining Sustainable Development Goals (SDG). Concurrently, the strategy produces a novel nonsynthetic fertilizer that aids in sustainable food crop production representing a paradigm step forward in the agriculture sector aligned with principles of circular bioeconomy.

2. Global waste generation

With ongoing industrialization, the technological improvements in the production sector have led to a significant increase in waste generation across various scales, including Industrial, municipal, Agricultural, and animal livestock, construction demolition, medical, radioactive, and other hazardous waste [15]. However, continuous waste buildup results due to technological limitations and inefficiency in waste handling consequently creating sustainability challenges as well as financial constraints worldwide. The authorities have failed to properly manage waste with economic growth showing waste accumulation does not appear to follow The Environmental Kuznets Curve (EKC). United Nations Sustainable Development Goals (UNSDG) aims at the environmentally sound management of waste despite the current progress pattern related to waste prevention, reduction, and recycling are insufficient to meet the goals in 2030.

High-income countries currently contribute 34 percent of global waste, amounting to 683 million tons with predicted daily per capita waste generation of 19 percent and middle- or low-income countries 40 percent in 2050. The regions experiencing the highest incremental rates in total waste generation are Sub-Saharan Africa, South Asia, the Middle East, and North Africa. In these regions, over 50 percent of waste is improperly disposed of, directly affecting biodiversity and human health [16] Figure 1 depicts the global waste composition, showing major portion comes from food and greens.

Food waste accounts for the highest proportion of 570 million tons annually [17] from various sources such as domestic, industrial, slaughterhouses, and catering [18] while high-income, middle-income, and low-income countries contribute 32 percent, 53 percent, and 56 percent to waste generation respectively. The percentage of food loss and waste (FLW) varies across different products and stages of the supply chain, including production, post-harvest, packaging distribution, and consumption [19]. Animal and livestock keratinaceous wastes [6] are reported 40 million tons annually with the contribution of USA, Brazil, and China mainly [6,9].

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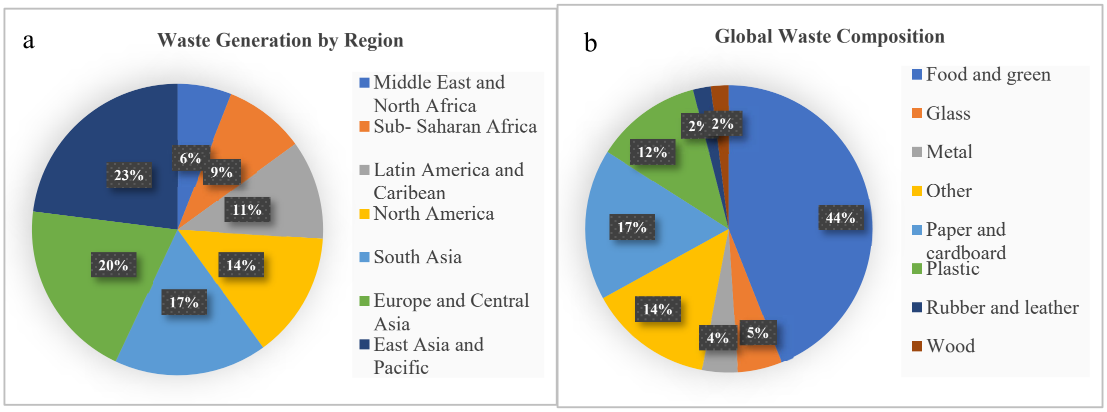

Figure 1. (a) Waste generation by region of the world (b) Global waste composition [17].

Proteinaceous wastes are disposed of through open dumping 33 percent, landfilling 37 percent, sanitary landfilling 8 percent, and incinerating 11 percent while only 19 percent is recycled for utilization [20]. However, these methods are inefficient in minimizing environmental pollution pressure and thus create a high impact on environmental sustainability and public health.

3. Food and Agricultural wastes as a major portion of waste generation

The proteinaceous food industry expands its production to satisfy the protein demand for a healthy diet, alongside proteinaceous waste and byproducts generation and accumulation is continuously escalating. The fish, poultry, and livestock industries contribute a greater portion to proteinaceous wastes.

Fish processing waste (FPW) is a major form of food waste disposed from the fishery industry accounting for 82.1 million tons of fish production in 2018 while 89 percent of the global total volume supplied from Asia in the last 20 years [4]. Depending on the level of processing or type of fish, 30-70 percent of the original fish is FPW [21] consequently, 35 percent of aquatic foods are disposed of as waste annually [22] and total FPW generation onboard in vessels and inland accounts 62 million tons [4]. FPW may include fish discards such as fish muscle trimmings (15-20%), heads (9-12%), viscera (12-18%), tails, fins, and skins (1-3%), scales (5%), and bones (9-15%) and dead, damaged fish or female fish in ornamental fish culture [5].

Poultry and livestock slaughterhouses collectively generate [11] 8.6 million tons of keratinaceous waste annually including feathers, fur, hooves, and horns [23]. Between 5-7 percent of the total mass of adult chickens comprises feather components, which are disposed of as wastes. Approximately 90 percent of this feather waste consists of protein components that are highly resistant to degradation. Therefore, feathers are typically disposed in landfills or through incineration [15,24]. This practice leads to significant energy consumption and environmental pollution.

Personal care industries generate million tons of human hair globally and it accounts for 1 million in respect to the United States (US) [7]. However, about 1 million kg of generation is used for preparing fashion and cosmetics beauty accessories, and hair care products in relation to India. The majority from urban and rural cut hair and further the byproducts from hair based cosmetic industry are bulk disposed into open dumps or burn. These create further environmental issues [8].

The leading countries for textile production are Australia, China, New Zealand, Iran, and Argentina, Australia contributes to 95 percent of the total wool fibers [25] and the industry extracts 1.15 million tons of wool fiber from sheep and other animals' fur [10] for the production of outer knitwear and woven attire. Novel emerging soft wool trend in "next to skin" knitwear has surpassed the traditional use of course fibers. However, the industry generates 2.5 million tons of waste during production annually and byproducts along with used woolen apparel collectively end up in disposal sites [26]. These are reused, recycled for the same value or lower value products, incinerated, or landfilled [27]. The protein-containing waste environmental impact and potential impact on waste management can be assessed through Ecological Footprint (EF) and Lifecycle assessment (LCA) [28].

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4. Challenges in proteinaceous waste management

Due to high protein content, these wastes degrade releasing unpleasant odour and providing a nutrient harbour for pathogen growth in turn leading to many human diseases and therefore considered hazardous [29]. Global accumulation of these wastes occurs due to the generation rate exceeding the disposal rate.

FPW ends up in either open land or sea dumps [22] about 54 percent of total FPW accounting for 27 million tons is sea-dumped during onboard processing [12], and 35 percent of FPW is landfilled or abandoned. Effluents from fish processing contain high levels of biological oxygen demand (BOD), Chemical oxygen demand (COD), Total suspended solids (TSS), Fat-oil-grease (FOG), pathogens, microflora, organic matter, and nutrients. These can harm coastal and marine environments [30] with less dissolved O_2 in coasts. The accumulation of organic matter beneath cage fish farms and the subsequent alterations in sediment conditions is another impact of marine fish farming [31,32] FPW load in a broader coastal area affects various levels of ecosystems, leading to a decrease in biomass, density, and diversity of benthos, plankton, and nekton, while also altering natural food webs [33].

Land dumping of keratinaceous waste pollutes fields and drinking water resources disseminating pollutants with runoff, and leachate [34]. High NO3-content is transferred to water bodies and causes eutrophication thus the effect on aquatic fauna. In turn, this leads to the spread of pathogens; Salmonella, E-coli pose a direct risk to human health, intensification increases the risk of pathogens [32] and the spread of rodents, and flies carry diseases and creates local nuisance. Open dumping also releases greenhouse gases such as CO_2, NOx, CO, and persistent organic pollutants (dioxins), heavy metals such as lead (Pb), copper (Cu), cadmium (Cd), chromium (Cr), nickel (Ni) and mercury (Hg), and ammonia (NH_3) and unpleasant odours creating public chaos. Open-burning of fur and hair emits toxic gases such as ammonia, carbonyl sulphides, hydrogen sulphides, sulphur dioxide, phenols, nitriles, pyrroles, and pyridines. Hair dust can be inhaled through the respiratory tract causing tuberculosis [35]. Incineration releases toxic emissions; GHG [34], VOCs, particulate matter along with heavy metals, and heat. Dioxin releases 30-56 percent of total gas emissions from feather incineration and bioaccumulates in food chains. These impacts on climate change and overall aesthetic aspects as depicted in Figure 2. More importantly, animal byproducts are not segregated under their risk Category recognized by the EU Animal By-Products Regulation (ABPR) in most countries thus these wastes possess an extra vulnerability.

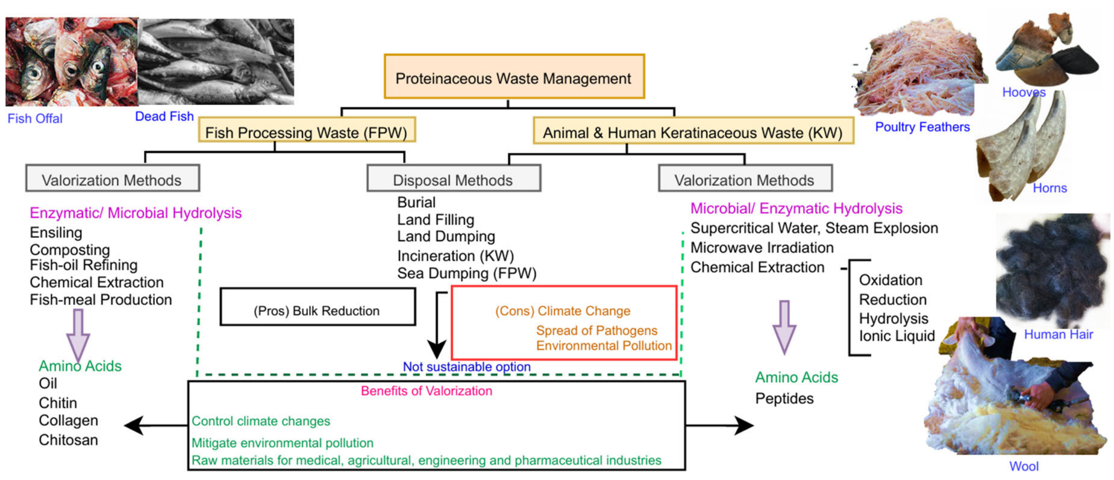

Figure 2. Negative impacts of Proteinaceous wastes on ecosystem.

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5. Current management of proteinaceous waste

The management needs control, regulatory, and monitoring procedures to safeguard the environment [31]. Waste management legislation ensures that waste is handled and disposed of, responsibly to protect public health, resources, and the environment thus covering management of all hazardous and non-hazardous waste types. Waste producers must make sure they follow the law by getting permits, filling out paperwork, and keeping records and prohibit engaging in activities that lead to penalties.

The Environmental Protection Act (EPA) 1990 aims to control waste disposal and pollution to safeguard the environment and public health thus minimizing businesses' environmental impact. The waste duty of care, outlined in section 34(7) of the Act, establishes guidelines for waste management, emphasizing handling, storage, transportation, disposal, pollution prevention, and sustainable development.

The Department for Environment, Food & Rural Affairs oversees the handling and disposal of animal by-products, including bones, fat, meat, and eggs. Guidelines are in place to ensure proper handling, processing, storage, and disposal of these products to safeguard both health and the environment. Animal by-products are categorized into three groups, which dictate their management approach; Category 1 (Animal by-product) ABPs are at high risk, Category 2 are intermediate and Category 3 are classed as low risk. Category 1 includes body parts liable to carry diseases, animals that contain high veterinary drug content, and wild animals, Category 2; digestive tract organs and Category 3; hides, skins, hooves, feathers, wool, horns, and hair that had no signs of infectious disease at death, aquatic animals, and aquatic and terrestrial invertebrates. A mixture of the above wastes may be treated as Category 1.

The EU Animal By-Products Regulation (ABPR) (1774/2002); regulation put forward by European Commission directives, several acts including an intra-species recycling ban for fur animals, fish, and specified methods for the burial, incineration, and burning of certain animal by-products. The disposal of untreated fish waste in landfills is forbidden, and retailers must implement ABPR-compliant methods, such as rendering, controlling collection, proper transporting, storing, handling, and processing during the disposal of animal carcasses or parts of animal carcasses. Deep ocean dumping of fish waste is allowed as effluent discharged into deeper waters or areas with strong currents will typically disperse over a wide area [31].

The UK Food Hygiene (Fishery Products & Live Shellfish) (Hygiene) Regulations 1998; Regulations related to the fishery industry in terms of importation, production, storage, since marketing further, hygienic waste handling, separation of offal/viscera from products for human consumption, regular removal of waste from on-shore processing facilities.

The Alaska Solid Waste Program; Solid waste regulations initiated in 1973 under the Department of Environmental Conservation (Register 47, October 1973, Title 18, Environmental Conservation, Chapter 60, Solid Waste Management, State of Alaska); (a) incineration is considered as a viable process (b) the disposal of decayable waste in areas subject to permafrost or leachate generation is restricted (c) violation of the regulations is subjected to penalties with fine or imprisonment for not more than one year or both [36]. Regulations on landfill disposal of fish waste and land application (effectively utilizing fish waste as fertilizer to agricultural lands and composting).

Apart from these, there are no government regulations or nongovernmental actions that have been imposed on waste management all over the world. And with the current practices and less management attention, the world cannot reach the SDG in the predicted period. Currently, management related to proteinaceous wastes is conducted through both disposal and valorization to utilizable products. Due to the benefits in a broad range, valorization is identified as the most sustainable waste reduction method compared to disposal (Figure 3).

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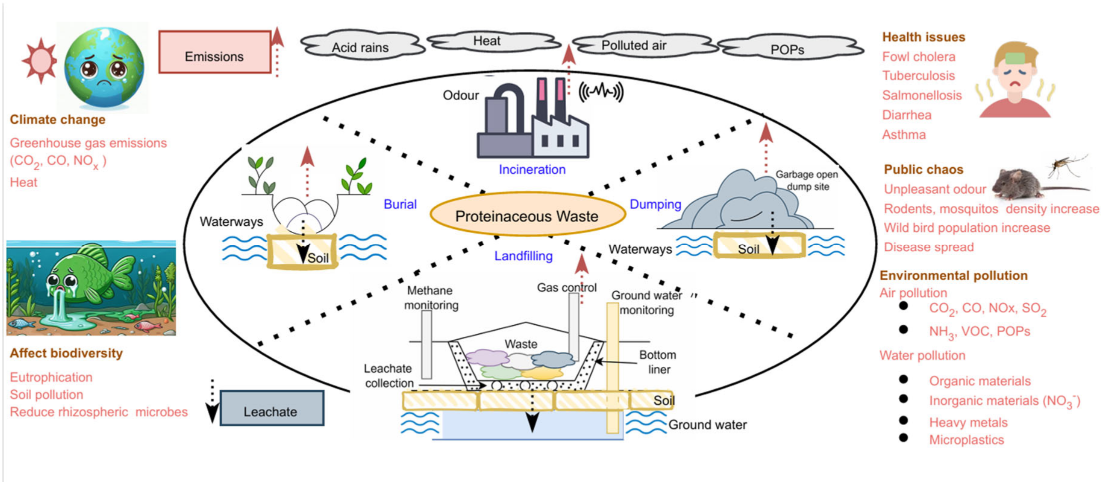

Figure 3. Proteinaceous waste management options.

FPW can be composted to obtain bulky fertilizer which exhibits non-phytotoxicity and increased contents of nitrogen, phosphorus, potassium, sodium, calcium, magnesium, and dry matter content to facilitate plants and soil despite exhibiting a reduced Ca:P ratio [37]. The process is an aerobic and biological method that yields a final stabilized humus-like product. Sawdust, wood shavings, crop residues, and wheat bran are often used bulking agents, and pH, moisture, bulk density, and C: N ratio are maintained to facilitate microbial activity. Fish compost shows poor consistency of nutritional values, time consumption for production, and bulkiness in fertilizer as major drawbacks.

Fish silage is produced by ensiling of FPW with organic acids or inorganic acids (sulphuric/ formic) and used as feed for pigs, poultry, and mink with a lower operating cost than fish meal. Utilizing organic acids is simpler since there is no requirement for neutralization and less corrosivity. When lactic acid bacteria are employed in fermentation, the culture density increases, cutting down the investment upon renewing the culture [38].

FPW has the potential to serve as a viable and environmentally friendly source for fish oil processing with desirable chemical, physical, and sensory characteristics [32,39]. Fish oil extraction can be conducted by hydraulic pressing, heat extraction, solvent extraction, acid fermentation, wet/ physical methods, and green extraction using supercritical CO_2, which are cost-effective and easy methods. Further novel eco-friendly techniques such as supercritical fluid extraction, enzyme extraction, microwave-assisted extraction, and ultrasound-assisted extraction, have been identified. The traditional methods exhibit drawbacks in terms of product quality, through degrading natural compounds under high heat, remaining toxic residues in the final product, creating environmental impacts due to the heat, and leaking organic solvents into the environment [40]. Fish oil can also be converted to non-toxic, biodegradable, environment-friendly biodiesel using chemical or enzymatic methods.

Fishmeal production from the fisheries by-products has increased drastically and around 6 million tons of fish waste have been used for fishmeal production [41]. It is estimated that 25 percent (1.23 million tons in 2008) of the total fishmeal produced is from fish by-products. Currently, 63 percent of the fishmeal is being consumed by the aquaculture industry, 25 percent by pigs, 8 percent by poultry, and 4 percent by other animals. Although fish meal is used as a feed ingredient, it contains a considerable quantity of microplastics (MPs). Many recent studies reported the availability of large MPs (> 1 mm), and viscera parts have exhibited 0.72 MPs/fish. Therefore, this method has limitations in the quality of the final product of valorization although practiced in waste management [42]. “Compact Fishmeal Plants” implemented on, on-board fishing vessels typically handle between 15 to 700 tons of raw materials per day [43].

Fish hydrolysate is produced from hydrolysis FPW through enzymatic; microorganisms or plant-extracted enzymes and chemical processes. Enzyme refining cost is reduced by employing anaerobic microorganisms producing proteases. In chemical hydrolysis, strong acids or bases

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together with heat are necessary. The disadvantages of fish hydrolysate are inefficient hydrolysis or uneven mechanical breakdown causing sedimentation, the difficulty of handling [44] unpleasant odour, and micronutrient loss such as Molybdenum (Mo).

To date, novel innovative applications using high-tech valorization approaches are developing to utilize these waste resources in various fields including medical, biotechnological, engineering, etc. Table 1 summarizes recently published literature about valorization methods of proteinaceous wastes in different fields.

Table 1. Summary of literature for valorization of Proteinaceous wastes**.**

Proteinaceous Waste	Valorization method	References
Keratin Waste	Keratin from human and animal sources; Chemical hydrolysis	[45]
Human Hair	Chemical hydrolysis using alkalis	[46]
Goat Hair	Biological hydrolysis *(Bacillus licheniformis* Strain ER-15)	[47]
Keratin Waste	Bioconversion (*Vibrio* sp.), hydrothermal and chemical hydrolysis	[48]
Keratin Waste	Chemical hydrolysis (tetramethyl ammonium hydroxide (TMAOH)	[49]
Feather Waste	Physical method-catapult steam explosion (ICSE), ICSE-keratinolysis process	[50]
Keratin Waste	Summarizes physical, chemical, enzymatic methods	[51]
Wool	Physical method (reduction method)	[52]
FPW	Enzymatic hydrolysis	[53]
FPW	Physical, chemical, and biological extraction methods	[12]
FPW	Specific methodology to use fish scale powder in improving the performance of asphalt	[54]
Wool	Biotechnological approaches, such as microbial or enzymatic pretreatment, and composting	[55]
FPW	Composting, hydrolysis, anaerobic digestion	[21]
FPW	Anaerobic co-digestion with a liquid fraction of hydrothermal carbonization	[56]
Feather Waste	Biological hydrolysis (*Streptomyces* sp. isolate SCUT-3)	[57]
Wool	Current approaches for raw wool waste management and unconventional valorization	[58]
Keratin Waste	Biological hydrolysis	[59]
Feather Waste	Biological hydrolysis	[60]
Keratin Waste	Summarizes valorization of keratin-based (wools, feathers, hair) waste	[61]

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FPW	Biological hydrolysis (early 68% of fish waste, 13% of molasses and 19% of scum) to produce biofertilizer	[62]
Keratin Waste	Different extraction methods to produce value-added products	[24]
Feather Waste	Different technologies to obtain high-value products	[13]
Keratin Waste	Different strategies for extraction and use in pharmaceutical and cosmetics industries	[63]
Human Hair	Specific method for extraction and use in biomedical and biotechnological applications	[64]
Human Hair	Extraction for biomedical applications	[65]
Horns, Hooves	Extraction for biomedical applications	[66]
Wool	Biological hydrolysis (*Bacillus pumilus* A1)	[67]
FPW	Fish protein hydrolysates	[68]
Feather Waste	Specific valorization methods to extract keratin for cosmetics	[69]
Feather Waste	Incineration to produce energy	[70]

Fish emulsion is processed by heat treating FPW at a temperature of at least 800C [21] to destroy pathogens, subsequently pressing the solid material yields the liquid fish emulsion rich in essential amino acids (EAA) and other nutrients [71,72]. Then stabilizes through acidification, using sulphuric, phosphoric, and organic acids [21]. According to literature, fish emulsion is successfully used to suppress Streptomyces spp. in potato scab and Verticillium dahlia in verticillium wilt reducing severity by 44-53 percent while increasing the tuber yield by 7-20 percent [73]. High heat used in the process decomposes protein creating an unpleasant odour and depleting micro and macronutrients making it disadvantageous.

Chitosan is prepared through FPW chemically treated by acids, alkaline or biologically treated by protease, and chitin deacetylase. Chitosan exhibits biodegradable and biocompatible properties, thus applied in the pharmaceutical, cosmetic, food, biomedical, chemical, and textile industries for water purification, and tissue engineering, further acting as antimicrobial agents to ease metal ion penetration [74].

There are chemical, biological, and physical methods of keratin waste valorization, to yield end products of keratin fiber, keratin scaffold, keratin films, and keratin hydrogels, fertilizers [61]. Chemical methods [75] are reduction, oxidation, ionic liquids, and hydrolysis, heating is commonly applied during chemical hydrolysis to promote a high yield, yet elevated temperatures can lead to the degradation of amino acids. The primary technique utilized for extracting keratin from hair and wool is the oxidation method. These employ a chemical cost for Peracetic acid, Ammonia, Hydrochloric acid, Hydrogen Peroxide, Sodium Metabisulfite, etc. In the reduction method, about 47 percent of protein content can be extracted, however, the formation of lanthionine reduces protein and (essential amino acids) EAA even causing toxicities. In the Alkali method, protein yield recovery is comparatively less and further impacts the (amino acids) AA content.

In microbial and enzymatic pathways, numerous fungi, actinomycetes, and bacteria species contribute to keratin extraction by producing keratinolytic and proteolytic enzymes such as keratinases, and Savinases (extract keratin from wool and feathers) [76] enzymatic hydrolysis involves minimal energy consumption and cost.

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As physical methods, the steam explosion is eco-friendly despite the heat destroys AA e.g., 50 percent cysteine (Cys), reducing the initial wool mass by about 18 percent, even though inefficient in cleaving the sulfide bond in protein degrading. Microwave irradiation can extract, 72 percent of feathers and 30-60 percent of wool [24]. The process of keratin degradation and extraction is highly efficient, with homogeneous heating within seconds. Around 71 percent of feather extraction can only be achieved through a temperature of 160 to 200 °C, thus disadvantageous due to high power consumption [77].

Although there are various currently practicing and potential strategies for proteinaceous waste management, through an impact analysis, we can decide that the most efficient cost-effective, and eco-friendly method is microbial fermentation. Moreover, this method yields a nutrient-dense liquid hydrolysate that can be used as a substitute nitrogen fertilizer for crops indirectly assisting in protecting and recovering soil from pollution through Urea. Consequently, this solves rising problems in two major sectors satisfying the circular bioeconomy.

Protein degradation in the biological conversion of FPW is carried out by acids and enzymes of fermenting microorganisms such as Lactobacillus spp. e.g., Lactobacillus plantarum. The culture is inoculated into molasses to obtain carbohydrates and incubated until a population of about 107 microbes/ gram of molasses is established and added to the minced fish [41]. Fermentation is more readily accomplished in areas characterized by consistently high ambient temperatures. The small-scale production is carried out more similarly to the above hydrolysate procedure with minor adjustments.

Keratin fermentation is the most promising approach and the genera include Bacillus; *Bacillus subtilis, Bacillus pumilus, Bacillus lichenifomis,* and *Bacillus cereus* [78], *staphylococcus, enterococcus* [79,80] belonging to 14 protease families [81]. As a popular bacterium, *Streptomyces* sp. SCUT-3 is used on an industrial scale which yields 8.1mg L^{-1} AA [57] fungi such as *Chrysosporium* [82,83] are further able to degrade keratin [57]. To isolate keratinase-producing microorganisms, the steps including sample collection, assay development, strain identification, and characterization are usually applied.

6. Potential for valorization and fertilizer formulation

All the proteinaceous wastes contain different amounts of crude proteins and degradation yields similar monomers. Therefore, the aforementioned biological conversion protocols can be employed to hydrolyze the wastes separately and mix together owing to their compatibility, so that the resultant nonsynthetic fertilizer is fortified with the highest quality and quantity of AA (Figure 4).

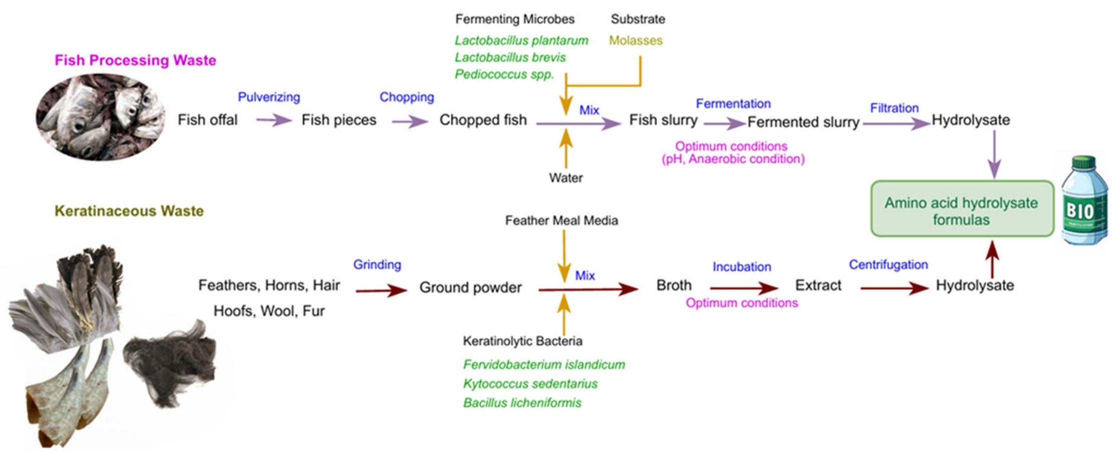

Figure 4. Diagram of the fortified hydrolysate production.

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This would be a paradigm change in modern agriculture which is targeting at sustainable solutions over conventional practices for crop nutrition. Around 50 percent of global farmers use Urea to satisfy crop nitrogen requirements [84] owing to various benefits [85]. However, Urea exhibits lower nitrogen use efficiency (NUE) and creates environmental pollution [86] due to leaching NO_3^-, volatilize as NH_3 and N_2O [87] even toxicities to microbes affecting soil-free amino acid (FAA) pool [88]. Crop NH_4^+ toxicity can occur due to overdosage causing plant growth arrest or death [89].

Nonetheless, the enriched fertilizer enriches all micro and macronutrients for plant growth and development, especially from FPW, and essential and conditional amino acids from all the proteinaceous wastes. These are absorbed through root hairs (soil drench) or leaf stomata (foliar) and improve soil biological and physicochemical characteristics [34]. (Table 2) illustrates the nutrients contained in FPW hydrolysate demonstrating the potential to use as fertilizer.

Table 2. Composition and characteristics [90].

Composition	Percentage (%)
1. Macro Nutrients	
Total organic carbon	25%
Nitrogen (N)	6.5%
Phosphorous (P)	1%
Potassium (K)	1.5%
Sulphur(S)	0.8%
Calcium (Ca)	15ppm
Magnesium (Mg)	15ppm
2. Micronutrients	
Sodium (Na)	1%
Manganese (Mn)	5ppm
Zinc (Zn)	17ppm
Copper	5ppm
Boron	7ppm
Molybdenum	0.5ppm
3. Parameters	
pH	6.5%
C:N ratio	4:1

6.1. Composition of FPW fertilizer

Over several years FPW fertilizers have been tested through a range of crop plants in the world; lettuce [21] radish, sorghum, sweet corn, peas, and soybean [91]. In India, a similar fertilizer with the trade name "Gunapaselum" has been tested on tomato plants with *Bacillus sublitis* starter culture [92] revealing a reduction in pH, enhanced CEC, OM, OC in soil, and major nutrients in the plant. In Africa and Ethiopia, a study demonstrated FPW fertilizers from Nile thilapiya can be used as an alternative for diammonium phosphate for tomato plants [93] and [91] found that FPW fertilizer reports better xylem and phloem functions in Solanum melongena, better yield in *Capsicum annuum*, and better stem girth, leaf sugar and vitamin C concentrations in *Centella asiatica*, compared to synthetic fertilizers (SF) [94].

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6.2. Composition of keratin waste

Keratin is a polypeptide strand containing different EAA, such as Glycine (Gly), Alanine (Ala), Serine (Ser), Valine (Val), Phenylalanine (Phe), threonine (the), tryptophan (Try), Isoleucine (Lle) together with Methionine (Met), Lysine (Lys), Leucine (Leu), Histidine [95]. Conditional AA contains Aspartic, Serine, Proline, Glutamic, Glycine, Alanine, Tyrosine, Arginine, and Hydroxyproline in significant quantities and further contains minerals [96] cross-linked by disulfide bonds and H bonds. These AA perform numerous physiological functions and structural makeup of crops such as cell formation, disease resistance, chlorophyll formation [97] phytohormone precursors, pollen growth, and protection [98] etc.

6.3. Introduce amino acid formulations from proteinaceous wastes

The plant nutrient requirement depends on the plant, soil, and environmental conditions, commonly, macronutrients, micronutrients (or trace minerals), and AAs are absorbed in varying quantities for overall growth and productivity. The enriched fertilizer is composed of nutrients in sufficient levels according to the reported literature that has measured plant performance with keratin and FPW fertilizer application separately. Therefore, the combination is predicted to enhance plant performance profusely. Different formulas altering the dosages of proteinaceous waste hydrolysates involved in the final fertilizer are suggested to be conducted in future directions.

7. Conclusions

According to the literature, in recent years continuous accumulation of wastes has occurred due to the rate of generation over valorization and disposal threatening environmental, public, and social stability. Food and green waste contribute to the highest proportion of these waste streams while the proteinaceous concentrated animal-based waste accumulation is hazardous as they supply nutrient-rich harbour for pathogens and social unrest. Further, the existing policy framework exhibits gaps in design and implementation thus insufficient to address all these wastes, Therefore, Sustainable Development Goals (SDGs) worldwide may be unattainable, and upon analysis using Life Cycle Assessment (LCA) and Ecological Footprint (EF), it becomes evident that many waste treatment options fail to reach sustainability standards.

Even though inedible protein substances are so far considered as wastes, recent scientific evidence proves that such proteinaceous wastes contain a high amount of amino acids which can be utilized through valorization to fulfill plant nutrient demand. Waste effluent is an undervalued resource due to the yielding of the common monomer/ nutrient upon hydrolysis that plants can easily assimilate. Microbial fermentation is considered a sophisticated valorization method however, it can be utilized to hydrolyze all types of proteinaceous wastes even though, no policies or regulations are imposed herewith.

Therefore, we highlight the following in terms of improving waste management with a systematic approach to extract nutrients from proteinaceous wastes. A broad legal framework should be imposed to address specific waste in each industry and attention should be drawn to improve valorization through bio-conversion techniques to optimize AA synthesis from proteinaceous wastes, formulate regulations for the collection and sorting of proteinaceous wastes, immediate transport, and storage of waste materials to delay spoilage, and implement compact hydrolysate plants for on-board fishing vessels.

Moreover, it is ideal to calculate the qualities of bioavailable AA of enriched hydrolysate and formulate recommendations to meet the AA demand of various crops based on their physiological and morphological differences in various growth stages. This method can be employed to minimize pollution from excessive urea usage in crop production, paving for sustainability leading to a paradigm change in modern agriculture while satisfying the concept of circular bioeconomy.

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