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Food waste in Indonesia: Assessing readiness for valorization

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ABSTRACT
In Indonesia, 23-48 million tons of food waste are generated annually, causing economic losses of IDR 213-551 trillion or around 4-5% of GDP. Food waste offers potential for valorization into products like animal feed, organic fertilizer, and biofuel but faces challenges such as technological limitations, high costs, and safety concerns. This study examines the safety of food waste-derived products for human and animal use, focusing on applications in animal feed, the food industry, cosmetics, bio-refinery, and organic fertilizers. Key processes include contaminant removal and safety assessments, though limited studies address physicochemical, microbiological, and toxic contaminant evaluations. Identified gaps in Indonesian regulations, particularly regarding safety standards, highlight the need for clearer guidelines and support for eco-friendly technologies. Enhancing these frameworks can ensure the safe and sustainable valorization of food waste.

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1. INTRODUCTION

According to the 2018 guidelines from the United Nations Food and Agriculture Organization (FAO), food loss denotes a decrease in the quantity or quality of food, due to policies and actions implemented along the supply chain, excluding activities within the retail sector, food service providers, and consumers. Meanwhile, food waste entails a reduction in the quantity or quality of food attributable to policies and actions implemented by entities within the retail sector, food service providers, and consumers. In Indonesia, based on an analysis conducted by the National Development Planning Agency (BAPPENAS), the volume of food waste reaches between 23 to 48 million tons yearly, approximately 115 to 184 kilograms per person yearly. This leads to economic losses ranging from IDR 213 to 551 trillion per year, equivalent to 4 to 5 percent of the country (GDP).

On a global scale, the FAO Food Loss Index for the year 2019 indicates that approximately 13.8 percent of the total food production, a significant amount of food was wasted in 2016 before it even made it to stores. The regions of Central and South Asia, as well as North America and Europe, were the major contributors, with respective loss percentages of approximately 20 to 21% and 15 to 16%. Specifically, Indonesia is recorded as one of the countries with the highest volume of food waste in the world, ranking second after the United States. Most food waste happens with root vegetables and oil-producing crops, followed closely by fruits and veggies, and then meat and animal products. It is important to acknowledge that specific data for Indonesia may differ and require further investigation.

Minimizing food loss and waste is essential not only for reducing production costs and improving the efficiency of the food system, but also for enhancing environmental sustainability by conserving resources and lowering greenhouse gas emissions. The efficiency of the food system is not the only concern, we must also consider the safety of utilizing food by-products and waste for other purposes to promote environmental sustainability. According to a 2013 study conducted by the FAO, greenhouse gas emissions from uneaten food significantly impact the environment, leading to substantial environmental costs. Notably, these costs do not account for the effects of changes in land use. Food waste contributes approximately 3.3 billion tons of carbon dioxide emissions annually, while the water and land resources used to produce wasted food are estimated at 250 cubic kilometres and 1.4 billion hectares, respectively. Food waste contains numerous biodegradable components that can promote the growth of harmful microorganisms, potentially causing illnesses and environmental contamination. Consequently, reducing food loss and waste is expected to positively impact water management, climate change, marine resources, terrestrial ecosystems, forestry, and biodiversity. In the context of Indonesia, reducing food waste can enhance productivity and profitability for stakeholders across the supply chain, including farmers, processors, transporters, retailers, and food service providers. According to data from the Ministry of Agriculture, approximately 48 million tons of food waste is generated annually, equivalent to a potential economic loss of IDR 300 trillion. Reduction food waste provides more food for suppliers to sell, lowers disposal cost, and an increase in consumer savings.

The Indonesian government is also enhancing the reduction of food waste and the exploration of new uses for food by-products through various policies and programs. Waste from agricultural and fisheries industries can serve as a source of functional or bioactive compounds with beneficial properties. For example, banana peels can be processed into flour as a high-fiber ingredient. The by-products can also be used as inexpensive animal feed or processed into organic fertilizer. Natural bacteria and fungi in organic food waste facilitate its decomposition, producing beneficial organic fertilizers that improve soil quality. Food by-products also have applications in the cosmetic industry, such as repurposing used cooking oil into soap, and in biotechnology, where fruit waste can be utilized for bioethanol production.

Food waste in Indonesia has significant potential to be repurposed into value-added products such as animal feed, organic fertilizer, and biofuel. However, its utilization still faces various challenges. Firstly, the stability of value-added components in the waste often varies depending on the type and processing methods. Secondly, large-scale technology for processing is still limited and costly. Thirdly, conventional extraction techniques are generally energy-intensive and expensive. Fourthly, many industries continue to rely on hazardous solvents during the extraction of components.

Regulations in regarding the utilization of food waste are governed by Law No. 18/2008 on Waste Management and Government Regulation (PP) No. 81/2012 on Household Waste Management. Food waste repurposed for animal feed is regulated by the Minister of Agriculture Regulation No. 14/Permentan/PK.350/2/2017. Meanwhile, in the case of organic fertilizer, the reference is the Indonesian National Standard (SNI) 19-7030-2004. The existence of these legal frameworks is crucial to ensure food safety, promote the utilization of waste, as well as protect public health and the environment.

Although efforts to utilize food waste are steadily increasing, research on its safety remains limited. This is crucial to address, considering the risks of the presence of contaminants and pathogens harmful to both human and animal health. Therefore, the objective of this study is to provide a current and in-depth overview of common strategies for analyzing and eliminating hazardous substances in food waste, facilitating safety assessment before further utilization. The expectation is that these efforts will ensure quality standards and support the implementation of a circular economy.

2. LITERATURE REVIEW

Food waste contains numerous phytonutrients and valuable bioactive compounds with significant added value in various applications such as food additives, nutraceuticals, therapeutics, and cosmetics when extracted. In Indonesia, the utilization of this waste has been implemented in several sectors. For instance, in the effort to prevent stunting in Tanjungmojo Village, Kendal, the community was empowered through the development of micro small and medium enterprises (MSMEs) dedicated to producing banana peel flour and processed products. This initiative aims to enhance community skills by providing knowledge on effectively utilize household waste. The outcome includes increased motivation and skills among the community in using locally sourced food materials and a reduction in household waste [1].

This study presents a summary of the current trends in utilizing food waste across various sectors, including supplements and food additives, pharmaceuticals, medicine, and livestock feed. It is important to note that evaluating the quality and safety of the valorized products should be a top priority in any strategy aimed at repurposing food waste. For a more comprehensive review of the different approaches to utilizing by-products and food processing waste in various applications, readers are encouraged to refer to recent review papers authored by the researchers mentioned in the original text. These papers provide a more in-depth analysis of the strategies employed in the valorization of food waste and highlight areas that require further exploration [2–6].

2.1. Food Sector

The food sector has emerged as one of the most innovative areas in utilizing food waste, driven by increasing awareness of sustainability and the economic potential of repurposing by-products. In Indonesia, various efforts have been made to transform food waste into high-value products, showcasing the integration of traditional knowledge and modern technology. These initiatives not only address environmental challenges but also create new opportunities in food production, functional ingredients, and alternative materials. Below are several examples of food waste utilization in different categories within the food sector.

1 Vegetable and fruit Waste
In Indonesia, vegetable and fruit waste is often processed into value-added products. For example, in Bekasi, a company named Honey Juice processes fruit peel waste from juice production into eco-enzymes through fermentation [4]. Furthermore, papaya peel waste is transformed into papain products adopted as a meat tenderizer [5]. The waste from red dragon fruit peel, an agricultural by-product, contains anthocyanins that can be used as a natural food coloring, offering a safer alternative to synthetic dyes [6].

2 Waste from the Dairy Industry
Explore the utilization of cheese whey as a source of protein to produce nata de whey. The results showed the significant impact of fermentation duration and differences in starter sources on the thickness and pH value of the resulting data.

3 Waste from Animal Product Processing
Animal by-products such as bones, manure, blood, carcasses, and skins are often processed into various useful products. For instance, the study was conducted on the processing of animal bones, particularly goat bones, into activated carbon [7]. Furthermore, abdominal fat from chicken, a by-product of chicken carcass production, is transformed into meat emulsion products [8].

4 In addition to animal manure and carcasses, a by-product of animal processing is the utilization of non-productive laying hens. In Indonesia, and the majority of Asian countries, non-productive laying hens are often transformed into culinary ingredients. In Western countries, the hens are processed into oil and protein-rich food for animal feed or pet food, as well as composted into fertilizer containing essential nutrients for plant growth [9].

5 Waste from processing fish and seafood products
In Indonesia, waste from the processing of fish and seafood has been transformed into various high-value products. Animal products waste such as fish scales has been processed into collagen through enzymatic extraction. This collagen is used as an additive in the food industry [10]. Additionally, shrimp heads and shells have been used in the production of natural broth powder, thereby serving as a substitute for MSG [11]. Finally, by-products from shrimp trawl fishing are processed into fish meal [12].

2.2. Animal Feed Sector

Using food waste as a raw material for animal feed has been a long-standing practice before disposing of it in landfills. However, waste from the vegetable and fruit industries has certain disadvantages due to its high moisture content, which often surpasses 80%, promoting the growth of microorganisms and increasing the risk of spoilage. As a result, additional processing is necessary to avoid contamination and guarantee the safety, nutritional value, and digestibility of the food waste when formulating livestock feed. These steps are crucial to ensuring that the feed is suitable for animal consumption and does not pose any health risks.

Some recent studies proposed new uses for grape pomace and lees from the wine-making industry as animal feed [16]. Furthermore, waste from the cocoa industry, such as cocoa bean shells, contains sufficient amounts of protein, minerals, and vitamins, making it a cost-effective material for livestock feed, usually after the remediation of theobromine [14]. Meanwhile, waste from coffee roasting can be used as a growth substrate for insect production, serving as livestock feed [15, 52].

A traditional practice is the utilization of raw and processed animal waste as an additive in livestock feed and pet food. According to the Fatwa MUI No. 52 of 2012, the feeding of livestock with impure items or animal waste is not permitted, specifically in certain farms such as those in Kampung Pojok Cigondewah, to ensure compliance with Islamic principles and maintain the purity of the livestock and their products [16].

2.3. Other Sectors

Bio-refinery products from food waste in Indonesia have significant potential to support the circular economy. Tropical fruit waste such as mango, durian, and jackfruit can be used for the production of chemicals, enzymes, and functional products. Furthermore to Prasetya et.al [17], reported that the extraction of pectin from mango peel possesses thickening and gelling properties. This pectin can be applied in the food and cosmetic industries. The utilization of food waste through biorefinery can generate value-added products while supporting the principles of circular economy. By-products from food, such as biofuel, biomass, biofertilizer, and chemicals, can be obtained from the biotechnological transformation of food waste through anaerobic digestion, fermentation, and composting [51]. Some studies show the utilization of palm oil waste as raw material for high-value-added products such as activated carbon, which can be used as a supercapacitor electrode material [18]. Additionally, abundant corn husk waste can be adopted as raw material for the food and livestock feed industries. There remains significant untapped potential in optimizing the utilization of corn husk waste for various applications.

The valorization of food materials into cosmetics has high potential considering the abundant availability of raw materials. According to Ambarwati [19], agricultural waste such as tropical fruit peels is rich in antioxidants and bioactive compounds beneficial for cosmetics. For example, mango peel extract contains phenolic compounds and carotenoids that function as natural antioxidants in skincare and hair care products [20]. Therefore, the utilization of agricultural and local food waste as natural cosmetic active ingredients can create added value for products while supporting the principles of the circular economy.

Numerous applications have been discovered to address the challenges of efficiently using natural resources and minimizing food waste. However, the safety assessment of these by-products is a critical issue, specifically for high-value waste obtained as food additives/dietary supplements, and animal feed, as previously discussed. According to Presidential Regulation Number 83 of 2018, guidelines related to valorization in Indonesia remain limited. While the government encourages recycling and reuse for managing marine waste, including plastic, specific regulations for the valorization of value-added products are lacking. Therefore, policies that promote private investment and multidisciplinary collaboration are needed to develop environmentally friendly valorization technologies. Additionally, legal certainty is crucial to ensure that new products such as chemicals, fuels, and cosmetics are produced, marketed, and distributed in compliance with regulatory and sustainability standards.

3. RESULTS

The valorization of food waste involves converting by-products into valuable materials such as animal feed, biofuels, and other commercial products. However, ensuring the safety and quality of these valorized products is paramount to their acceptance and usability. This section presents two tables summarizing the results of rigorous safety studies that evaluate both the physicochemical and microbiological properties of these products, as well as an assessment of potential contaminants that might be present.

Tabel 1 outlines the results from various studies that have investigated the safe reuse of different food waste components. Each entry in the table describes the type of food waste examined, the beneficial compounds identified, the processing methods applied, and the outcomes of safety evaluations focusing on physicochemical and microbiological parameters. Table 2 describes the evaluation of contaminants in valorized food by-products following the safety assessment, it is also crucial to examine the potential contaminants that could be inherent or introduced during the processing of food by-products. Tabel 2 details the types of by-products assessed, the processing techniques used, the specific contaminants investigated, and the methods applied for their detection and quantification, providing a comprehensive overview of the potential risks associated with these valorized products.

Table 1. Application of physicochemical and microbiological safety studies on valorized food by-products.

Matrix	Interesting Compounds	Processing	Physicochemistry	Microbiology	Reference
Coffee Silverskin	The good stuff in food waste includes things that help with digestion, build strong bodies, and have special powers that can help keep us healthy	*Extrusion*	Moisture, ashes, proteins, fat sugars, carbohydrates	The study looked at various types of bacteria, including those that thrive in air and moderate temperatures, as well as those that can cause illness, like Salmonella and E. coli	[35]
Banana peel flour	Food waste is packed with helpful things like fiber, proteins, and healthy fats, as well as special helpers like antioxidants and vitamin K	*Drying + Grounding*	Moisture, carbohydrates,fibers, sugars, chloride, lipids, color, texture profile		[23]
Coffee cascara	The leftovers of food processing are rich in various nutrients like healthy fats, sugars, fiber, minerals, and vitamins	*Drying*			[24]
Olive Pomace	The valuable parts of food waste include fiber, healthy fats, complex carbohydrates, and special plant compounds		Solubility, moisture, WHC,OHC, fiber, fatty acids, proteins, lipids, ashes	A special test was used to see if certain substances could cause genetic mutations	[25]
Snow crab cooking waste water	Food waste contains important nutrients like proteins, minerals, and antioxidants, as well as nice smells	*Filtration + reverse osmosis*	Moisture, WHC, OHC, NSI,ashes, proteins, lipids, sugars,volatile compounds,aminoacids	The study examined several types of bacteria that can cause illness, including Bacillus cereus, Clostridium perfringens, and Salmonella	[26]

Matrix	Interesting Compounds	Processing	Physicochemistry	Microbiology	Reference
Vegetable By Products	Food waste has the potential to provide helpful compounds that can benefit our health	*Drying (microwave,PCD, static and rotatory oven)*	Moisture, ashes, proteins, fiber,fat, starch, sugars, minerals	The study looked at several types of bacteria that can cause illness, including Salmonella, Listeria, and E. coli, as well as those that can cause other problems, like mold and yeast	[11]

Table 2 Evaluation of contaminants in valorized food by-products

Safety Matrix	Mandated Products	Processing	Containment	Techniques for Assessment	Incident	Reference
Palm Oil leftovers	Helpful fats	Processes to clean and purify substances, including removing impurities, making them white, getting rid of bad smells, and adding hydrogen	Harmful chemicals that can cause problems	A way to test for tiny amounts of substances using a special machine	-	[51]
Insects grown on coffee and tiny plant leftovers	A mixture rich in protein and healthy fats	A method that uses electricity and a special tool to break down substances and then tests them using a machine that can detect tiny amounts of metals	Bad metals like lead, mercury, and arsenic	A method that uses heat and a special tool to break down substances and then tests them using a machine that can detect tiny amounts of metals	0.010—0.76 mg/kg	[52]

Safety Matrix	Mandated Products	Processing	Containment	Techniques for Assessment	Incident	Reference
Puffy fish skin	A type of protein that helps with skin and bones	A way to use high-voltage electricity to help extract substances	Poisonous substances that can hurt us	A way to test for a poisonous substance called tetrodotoxin by breaking it down with acid and then using a special test	"- Heavy metals:0.042 — 1.152 mg/kg - Tetrodotoxin: 1.7 MU/g"	[29]
Extracts from olive tree leaves	Special helpers found in plants	A method that uses a special tool to clump together tiny particles and then filters them out, followed by testing using a machine that can detect tiny amounts of substances	A mix of 15 bad chemicals and 10 harmful metals	A method that uses a special liquid to extract substances and then tests them using a machine that can detect tiny amounts of pesticides and metals	"- Pesticides: < 0.002 mg/kg - Metals: < 52 mg/kg"	[30]
Wastewater from olive processing	Many special helpers found in plants	A way to test for certain substances using a special machine that can extract them from a solid material and then tests them using a machine that can detect tiny amounts of substances	Pollutants that come from living things	A way to measure the amount of oxygen needed to break down substances in water	-	[31]
Leftovers from durum wheat processing	A mix of healthy fats and special helpers	A method that uses a special tool to extract substances from a liquid and then tests them using a machine that can detect tiny amounts of substances	Bad fats that can cause problems	A method that uses a special machine to extract substances from a solid material and then tests them using a machine that can detect tiny amounts of substances	9.8—594.3 mg/kg	[32]

Safety Matrix	Mandated Products	Processing	Containment	Techniques for Assessment	Incident	Reference
Used grain and yeast from brewing	A mix of protein, fiber, and important vitamins and minerals	A way to test for certain substances by freezing them, drying them, and then using a special tool to extract them, followed by testing using a machine that can detect tiny amounts of substances	Fungi that can make us sick	A way to test for a poisonous substance called ochratoxin A and other similar substances using a special liquid and a machine that can detect tiny amounts	<2 mg/kg	[26]
Grape peels	A mix of fiber and special helpers	A method that uses a special machine to extract substances from a solid material, breaks them down using water.	A type of poison that can hurt us, as well as bad chemicals and metals	A method that uses a special tool to extract substances and then tests them using a machine that can detect tiny amounts of pesticides and metals	"- Ochratoxin A: 0.32µg/kg - BIAs: < 84.93 mg/kg - Pesticides: < 4.91mg/kg - Metals:937.96 mg/kg "	[19]
Soybean leftovers	Special plant compounds	A way to test for certain substances by extracting them from a liquid and then testing them using a machine that can detect tiny amounts of substances	Two types of harmful chemicals that can form during processing	A way to test for substances using a special machine that can detect tiny amounts of substances and a special tool to extract them	-	[33]
White grape leftovers	Various helpful compounds	-	11 types of chemicals used to kill fungi	A way to test for poisonous substances called dioxins and PCBs using a special machine that can detect tiny amounts	<1.007 mg/kg	[34]

Safety Matrix	Mandated Products	Processing	Containment	Techniques for Assessment	Incident	Reference
Coffee skin leftovers	A mix of special helpers, fiber, and other good stuff	-	A type of poison that can hurt us, as well as bad chemicals that form when plants break down	A method that uses a special tool to extract substances and then tests them using a machine that can detect tiny amounts of metals and other substances	"Phytosterols oxidation products:1.14 g/kg - Ochratoxin A:18.7—34.4 µg/kg"	[35]
Oil from fish	Helpful fats	-	A mix of harmful chemicals like PCBs, PBDEs, and others	A way to test for a poisonous substance called ochratoxin A using a special test	<14.70 ng/kg	[36]
Cocoa leftovers (husks, beans, etc.)	Helpful fats	-	A type of poison that can hurt us, specifically types B1, B2, G1, and G2	A method that uses a special liquid to extract substances and then tests them using a machine that can detect tiny amounts of substances	<13.3 µg/kg	[37]
Fish leftovers	Special healthy fats	-	A mix of harmful chemicals like PCBs, PCDDs, and others	A way to test for substances using a special machine that can detect tiny amounts of substances and a special tool to extract them	- POPs: <2 mg/kg - Metals: 805 mg/kg	[38]
Oil from fish	Helpful fats	-	A mix of harmful chemicals like PCBs, PBDEs, and others	A method that uses a special tool to extract substances and then tests them using a machine that can detect tiny amounts of pesticides and metals	- PCDDs and PCDFs:< 0.47 TEQ ng/kg - PCBs, PBDEs, OCPs:< 6.85 µg/kg	[39]
Oil from fish	Helpful fats	-	A mix of harmful chemicals like PCBs, PCDDs, and others	A way to test for poisonous substances called POPs using a special machine that can detect tiny amounts	<65.4 ng/kg	[40]
Oil from fish	A type of acid and	-	A mix of harmful chemicals	A method that uses a special liquid to extract substances	-	[41]

Safety Matrix	Mandated Products	Processing	Containment	Techniques for Assessment	Incident	Reference
	special helpers		like PCDDs, PCDFs, and others	and then tests them using a machine that can detect tiny amounts of substances		

4. DISCUSSION

4.1. Food safety assessment

Agricultural waste including rice straw, corn cobs, and tropical fruit waste such as mango and durian have the potential to be used in the production of value-added products, namely chemicals, enzymes, as well as biofuels, through the biorefinery concept. However, regulations in Indonesia regarding the application remain considerably limited. Policies related to plastic and marine waste management are currently in existence, but there are no specific rules regarding the conversion of waste into products.

To foster environmentally friendly technologies for waste utilization, policies enhancing private investment and multidisciplinary collaboration are needed. Other challenges include public acceptance, food safety assessment, and the implementation costs of new technologies. Further study on the safety of products derived from waste utilization is required. The topic should be discussed in detail by dividing it into 3 parts, namely Physicochemical and quality studies, Microbiological studies, and Contaminants assessment. This will include benchmarking from various secondary data sources through a literature review process.

4.2. Physicochemical and quality studies

Assessment of food through physicochemical and quality studies in Indonesia or ASEAN, with a focus on new food or animal feed materials obtained from food waste valorization, comprises various aspects such as product development, quality improvement, and waste management. The development of new food or animal feed products often entails the substitution of ingredients. For instance, a study developed F100-based cookies with the substitution of pumpkin flour and banana flour. This study was conducted using experimental methods to determine differences in energy, protein, and fat content, as well as the acceptability of the final product. The results showed that the substitution of pumpkin and banana flour could impact the energy, protein, and fat content in cookies, as well as the overall acceptability of the product [23]. The improvement of food or animal feed product quality can be achieved through various methods, including fermentation. A study indicated that the addition of granulated sugar to market vegetable waste can enhance the quality of rabbit feed. The fermentation process was conducted for 7 days, and the results showed good quality in the produced feed [24]. Effective food waste management is a crucial aspect of food assessment. In Indonesia, the phenomenon of food waste reaches 300 kg per person yearly, ranking the country second in the world for large-scale waste, necessitating high management [25]. A method adopted was conductive drying, which can reduce the mass of food waste [22]. Investigation and innovation in this field can contribute to enhancing the quality of food and animal feed products while reducing the negative environmental impact of the waste [42].

Various easily accessible sspecialized methods have been employed to examine the issue to determine the physicochemical properties of novel valorization material and food products derived from food waste, based on global literature reviews summarized in Table 1. These materials are utilized for human consumption and other applications. Common parameters measured include moisture content, acidity, ash content, color, and nutritional composition such as fiber, carbohydrates, fats, and proteins. More specific analyses like texture profiling, Water-Holding Capacity (WHC), and Oil-Holding Capacity (OHC) have also been conducted for particular uses. To ensure the product remains stable and safe from harmful microorganisms, it's essential to monitor the water levels, as excessive moisture can lead to the growth of unwanted bacteria incorporate drying steps to decrease moisture content below 12% [25,26]. However, the effects on the beneficial compounds and the components of the by-products are still a concern during implementation. A study by Farahdiba et al. [22] evaluated the formation of Some unwanted chemicals can affect the taste and safety of a new drink made from leftover coffee. When coffee husks are dried in the sun, a chemical reaction happens that turns proteins and sugars into helpful compounds that can fight off bad things like germs and inflammation. But this process also creates a potentially harmful substance, although luckily, it's not too much to worry about according to European standards are 450 and 900 micrograms per kilogram, respectively, indicating the process's ability to produce a safe and reliable product is crucial. Moreover, physicochemical evaluations demonstrate the stability and safety of these valorized products, ensuring that they meet regulatory standards and are fit for consumer use. Transforming waste through processing can boost its ability to counteract oxidation and nutritional. The final drink's characteristics, such as its color and texture, are often evaluated these factors play a significant role in successfully introducing new products to the market. and their association with food safety, quality, and the stability of bioactive compounds.

To assess the rancidity of food products derived from waste, tests like peroxide and anisidine were performed, which measure oxidation products such as peroxides and aldehydes. On the other hand, increasing acidity by adding organic acids during processing was used as an alternative method to preserve meat waste. Investigated the impact of incorporating citric and malic acids into sheep buchada on the study looked at how safe and nutritious the final product was, as well as its physical and chemical properties. It found that adding a small amount of certain acids made the product better at fighting off damage, reduced the amount of bad fats, and made it less hospitable to harmful germs. This made the product last longer without affecting its quality or taste. The study also looked at other properties, like how well the product dissolves in water and holds onto liquids, to see if it was good enough to use [24,27] . For instance, researchers have assessed the how well the product could hold onto water and oil of processed snow crab waste intended for enhancing flavor when developing novel products. These metrics, which measure the ability of proteinaceous substances to retain water and oil, demonstrate the applicability of the treated waste in producing thickened foods (leveraging WHC) as well as in the meat and confectionery sectors (utilizing OHC). Lastly, it's important to note that evaluating nutritional quality is vital in nearly all studies involving physicochemical analyses. In this regard, the most frequently measured and highly prized components in the waste materials under investigation are proteins, lipids, carbohydrates, and dietary fibers. Additionally, other factors such as volatile compounds and mineral content are also considered in certain cases [22] or mineral content [30–32]. When it comes to measuring proteins, scientists often rely on the Kjeldahl method, which involves breaking down the sample with a strong acid to release nitrogen, which is then measured using a titration technique. However, some studies have also used a more advanced technique called High-Performance Liquid Chromatography (HPLC) to precisely measure the concentration of specific compounds in the valorized products. A special kind of testing that uses light to detect tiny particles was used to analyze the samples to quantify both total and free amino acids. The study looked at whether the process of turning waste into something useful was good enough and if the end result was of high quality [26,32]. When evaluating fat content, researchers have relied on a weight-based method using a Soxhlet extractor and a solvent such as petroleum ether. Additionally, they've employed techniques that separate and identify the individual components of fats, allowing them to understand the specific types of fatty acids present [31,33]. While the fatty acid profile has been analyzed using chromatographic techniques [3]. To figure out how much dietary fiber is in a food, researchers have used a method that combines enzymes and weight measurements called High-Performance Liquid Chromatography (HPLC) to measure the amount of free sugars in a food. This method is paired with special detection tools that use ultraviolet light and color to identify the sugars. When it comes to minerals, scientists have measured the total amount by burning the food in a special furnace and then analyzing the ash that's left behind [31,33]. To get a more detailed picture of the individual minerals, they've used specialized techniques like inductively coupled plasma emission or mass spectrometry [30]. For the most part, researchers have employed well-established techniques without additional modifications, unless certain aspects are especially crucial to ensuring the quality or safety of the novel applications being developed, in which case tailored analytical methods must be devised.

4.3. Microbiological studies

In Indonesia, ensuring microbiological safety is of utmost importance in the food industry, especially when it comes to utilizing food waste to increase its value. Plant-based waste materials, including fruits, nuts, grains, and other non-perishable foods, can become a breeding ground for if the conditions after harvesting are not properly managed, it can lead to the growth of unwanted microorganisms, resulting in a failure to adhere to quality standards. In contrast, animal-based waste is cforategorized into three different groups based on the level of epidemiological risk. Category three consists of low-risk materials that can These materials can be repurposed for creating nutrient-rich soil or producing renewable energy production, with or without further processing. Categories one and two, on the other hand, contain high-risk materials that require drastic measures, such as incineration, to eliminate pathogenic microorganisms. Unfortunately, in Indonesia, there is a lack of comprehensive microbiological safety assessments for valuable waste materials. As a result, a global literature review will be conducted to gain insights into how microbiological studies are performed on products derived from valorization processes.

As shown in Table 1, microbiological studies have been conducted on various types of waste, including vegetables [31,34], meat [26], and shellfish [46]. Regardless of the type of by-product, The studies examined a comparable set of microbes across the majority of cases. For example, Salmonella testing is conducted on almost all material types, and the products analyzed were found to be free of this pathogen, in compliance with applicable domestic and global regulations. Other bacteria like Listeria and E. coli showed analogous outcomes when assessed in diverse plant-based waste materials sourced from industries such as potato, cider, wine, horticulture, bread and coffee production. The valorization processes successfully removed these potentially dangerous bacteria from all tested products while still meeting the necessary safety criteria, as evidenced by the absence of both organisms in the end products.

One of the primary obstacles faced over time is obtaining the necessary reference values to evaluate the appropriateness of the waste materials obtained. There is a lack of specific regulations addressing this issue, which has led to the use of limits established for the original materials or similar matrices as reference data. For instance, thefor safety evaluation of the leftover material from recycling snow crab wastewater, which has been enriched through osmosis and then freeze-dried, is crucial. with flavor utilized the standards applied to dry foods as a benchmark [35]. The comparison revealed that the concentrations of The amounts of certain bad bacteria, like Bacillus cereus, Staphylococcus aureus, and Escherichia coli, were very low. Additionally, Salmonella was not detected in the residue, which is consistent with the guidelines for dry foods in Canada. These findings demonstrate the importance of establishing appropriate reference values and regulations to ensure the safety and suitability of valorized food waste products.

A similar strategy was followed by Zabed et al. [46], who conducted a study to assess the potential of using the outer layer of coffee beans as a supplement to enhance the nutritional value of cereal-based products. In the absence of specific regulations for this type of waste, the researchers referred to standards established in Mexico for roasted coffee and cereal-based additives as reference points. For roasted coffee, a strict limit of fewer than three units per gram is set for a specific type of bacteria. Meanwhile, for cereal-based additives, acceptable limits for various types of bacteria and molds are set at 500,000, 500, and 500 CFU/g, respectively. Microbiological analyses revealed that the concentrations in the tested waste were below these limits, suggesting its suitability as a food additive. However, the lack of reference values for yeast and Staphylococcus aureus made it difficult to fully evaluate the obtained data. This highlights the need for further studies to establish specific regulations for these types of waste

Another challenge in evaluating the safety of food by-products from a microbiological perspective lies in distinguishing between the natural growth of specific microorganisms during processing and the presence of unacceptable conditions that may lead to contamination and pose health risks to consumers. This issue was addressed by Zabed et al. [46] in their study on the valorization of cassava starch waste, which is acidic, by using it as an ingredient in fiber-rich food products. While Brazil has specific regulations regarding the maximum allowable amounts of certain bacteria and the required absence of a particular type of bacteria, no quality parameters were established for other microorganisms evaluated. This ambiguity is reflected in the total aerobic mesophilic bacteria values, which ranged from 1×10^1 to 6.5×10^3 CFU/g. It raises concerns about whether the cleanliness during fermentation was maintained or whether the natural bacteria in cassava starch contributed to fermentation, producing its characteristic tangy flavor. This highlights the need to clarify quality parameters for fermented by-products, such as cassava, to provide strong support for their valorization. Moreover, the absence of clear regulations not only limits the potential for enhancing the value of agro-food industry waste but also compromises the safe consumption of the resulting products.

4.4. Contaminants assessment

Food contamination is a prevalent problem in the food industry, which can occur at various stages, such as crop cultivation, livestock farming, food processing, and plant storage. Numerous harmful substances, including both organic and inorganic compounds, can be present in food ingredients and pose a significant risk to consumer health, even at very low concentrations. As a result, the scientific community and international authorities are making substantial efforts to assess the actual risks associated with the presence of these contaminants in food products. Furthermore, researchers are actively working on developing more sensitive methods to detect these substances at low levels and creating more effective procedures to prevent their presence in the final products. These initiatives aim to ensure food safety and protect consumer health by minimizing the risks associated with food contamination [22].

The potential for contamination also extends to the field of food waste valorization. When utilizing food waste to develop new products and applying various processes to achieve these objectives, concerns may arise in different areas, such as environmental and food safety. Consequently, it is essential to thoroughly evaluate impact on the quality and safety of the final products [22]. In this context, assessing There's a risk of contaminants from the raw materials making their way into the final products and the formation of new hazardous substances during processing becomes crucial. However, similar to physicochemical and microbiological analyses, Research in this area is limited, and checking for organic contaminants in recycled waste isn't a standard practice in these types of investigations. This highlights the need for more research to ensure the safety of products derived from food waste valorization processes.

Table 2 presents a compilation of representative examples that demonstrate how the contaminants evaluated in each case are dependent on the type and origin of the food waste. For plant-based products, assessments of pesticides [26,34–35] and toxins [32,36–37], have been primarily conducted There's a risk of contamination happening while the food is growing or being stored away. In the case of fish waste, several persistent organic pollutants have been investigated because of known contamination in marine environments and The same risk is present when the food is being processed and turned into a product [38–41]. Metals found in animal waste [42,43], Various other harmful substances have been found in different types of food [41, 44].

The study conducted by Yunus & Elsa [47], and illustrates an example of assessing certain harmful substances can form during food processing, particularly when making certain types of acids, toxins, and chemical byproducts. The research investigated the formation when extracting certain compounds from soybeans, some unwanted chemicals can form during the process. This happens when using a specific method that involves heating and breaking down the compounds with acid., which led to the significant production of two unknown compounds alongside the desired isoflavones. Using special tools to analyze the compounds, two harmful substances were identified. These substances are not safe for use in food or medicine. Varying hydrolysis times were assessed to examine their impact on the transformation process, with longer times yielding increased aglycone areas but also a higher quantity of 5-ethoxymethyl-2-furfural. As a result, a subsequent purification process was proposed, incorporating A special process was used to extract and purify certain compounds, which involved using a liquid and a solid to separate the good stuff from the bad. This process worked well and resulted in a high-quality final product for food applications. Although the furfural compounds produced exhibit toxic properties, they can be isolated and utilized The valuable compounds found in soybeans can be used to make biofuel, which makes this approach a good idea for the environment and the economy.

Analogous challenges emerge when enriching bioactive compounds, as the extraction process is frequently A technique was used to separate and concentrate the good stuff from food waste. Nevertheless, if adequate selectivity is not exercised, when processing raw materials, it's possible for contaminants to become more concentrated, which is why it's important to check for both the good and bad stuff [42], [44–45]. In this regard Chen et al. [29] examined the effects of ethanol extraction on the levels of contaminants such as ochratoxin A, biogenic amines, pesticides, and metals in grape skin extracts. The study found that ochratoxin A migrated at a rate of 36-88% during extraction, but the concentrations detected in the final extract were below regulatory limits. Biogenic amines, including ethanolamine and ethylamine, were also detected in both waste streams, with some residues exceeding EU limits for wheat. Heavy metals were not detected in the extracts, but lead was found at trace levels in dried skin, and cadmium exceeded EU limits [55]. A study demonstrated the effectiveness of a decontamination process for fish oil waste, achieving removal efficiencies of 76-96% for polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans, 89-99% for PCBs, and >86% for polybrominated diphenyl ether [28]. However, the lack of specific reference values for waste-derived foods limited the accurate safety evaluation of the valorized product.

In addition to the mentioned issues, it should be considered that some commonly used wastes tend to accumulate or develop higher levels of hazardous substances compared to the whole origin materials. This is often observed in seeds or peels of various fruits, showing higher levels of hydrophobic organic contaminants, For instance, research highlighted the accumulation of hazardous substances in certain waste materials, such as grape seeds and seed oil, which can hinder valorization [22]. Similarly, animal by-products may accumulate heavy metals in specific organs, posing obstacles to their valorization.

The findings revealed that grape seeds and seed oil had higher concentrations of contaminants compared to the pulp, attributed to the lipophilic properties of the hazardous substances. This emphasizes the need for careful consideration of waste material selection for valorization [43,46]. Numerous studies have evaluated the quality and safety of fish oil and other waste intended for aquaculture feed, highlighting the importance of assessing the presence of hazardous substances and their migration to livestock and consumers [31,39,43]. The EU has set maximum residue limits for various food commodities, but the permitted limits on fish are higher than for others, particularly for products intended for infants and children. It is essential to evaluate the presence of hazardous substances and develop strategies to reduce their incidence in valorized waste without compromising the benefits provided in the food chain [39,41]. Short-path distillation is a frequently applied decontamination procedure that minimizes the number of collisions molecules undergo after evaporation, reducing the time sensitive compounds spend in the equipment [49]. However, further research is needed to improve the precision of this technique and prevent the loss of valuable nutrients.In this method, a very low-pressure environment and a short distance between the heating and cooling surfaces minimize the number of collisions that molecules undergo after they evaporate. This reduces the time that sensitive compounds like cholesterol, vitamin E, vitamin A, and vitamin D spend in the equipment, which helps prevent them from breaking down. However, more research is needed to improve the precision of this technique and prevent the loss of valuable nutrients.

4.5 Comparative Analysis of Food Waste Valorization Strategies

To enhance the evaluation of Indonesia's readiness for food waste valorization, this study integrates a comparative analysis of strategies employed in regions with similar socio-economic and environmental conditions. Countries such as India and Brazil, facing parallel challenges with high food waste volumes, limited technological infrastructure, and resource constraints, have initiated diverse valorization methods. In Malaysia biodiesel production is evolving to address environmental concerns and improve efficiency, driven by increased commercial adoption worldwide [48]. The review highlights that diverse feedstocks (e.g., vegetable oils, animal fats, and waste oils) are central to enhancing biodiesel sustainability [50]. It evaluates various synthesis methods—such as transesterification and thermal cracking—for environmental and economic feasibility, and assesses purification strategies like wet washing and membrane separation for their effectiveness and ecological impact. Technological advancements are shown to play a key role in overcoming traditional production challenges, suggesting that these innovations improve the sustainability, cost-effectiveness, and scalability of biodiesel production [53].

In Nigeria, significant challenges in managing vegetable waste arise primarily due to heavy reliance on landfilling and minimal recycling. However, sustainable practices like composting and biogas production show promise in reducing landfill use and providing renewable energy [54]. Pilot composting projects have notably decreased landfill reliance and increased community participation in waste management initiatives. The study emphasizes the importance of policy support and greater community involvement to expand these sustainable practices, suggesting that such an approach could serve as a model for other developing cities with similar waste management issues. By examining these examples, the article can present a broader perspective on the viability of different valorization pathways and regulatory approaches, highlighting lessons that may inform Indonesia's policy framework and technological advancements.

5. CONCLUSION

In conclusion, the significant economic losses experienced in Indonesia due to food loss and waste, reaching IDR 213-551 trillion or 4-5% of GDP, signifies the importance of reducing both phenomena to enhance the efficiency of the food system and promote environmental sustainability. As the second-largest contributor to these phenomena globally, Indonesia faced challenges in using waste across various sectors, including food production, animal feed, organic fertilizer, and others. The constraints included the stability of value-added components, technological limitations, and high costs. Therefore, policy support and investment were crucial for the development of environmentally friendly technologies. Assessing food safety in products derived from the valorization of food waste was essential, covering physicochemical, microbiological, and contaminant aspects. Existing regulations in Indonesia, such as those governing waste management and the reuse of agricultural by-products, provide foundational standards for food waste valorization. However, significant gaps remain that hinder effective implementation. Current legislation lacks specific guidelines for the safe processing, handling, and distribution of valorized food products, particularly concerning permissible contaminant levels, labeling requirements, and monitoring standards. To address these gaps, it is recommended that Indonesia establish detailed safety protocols tailored to different types of food waste and valorized products. Additionally, a centralized regulatory body could oversee cross-sector coordination, ensuring consistency across environmental, agricultural, and health standards. Clearer guidelines on private sector incentives, tax relief, and public-private partnerships could further drive investment in sustainable technologies. These policy improvements would support safer, more efficient valorization practices and strengthen Indonesia's readiness to integrate food waste valorization into a circular economy framework.

Further studies and the establishment of specific standards related to the safety of valorized products are necessary. One key observation from this investigation is that reducing food loss and waste was not only about economic efficiency or environmental sustainability, but ethics and social responsibility. In a world with limited resources, where many struggle to access sufficient food daily reducing food loss and waste reflects a more ethical and socially responsible approach to resource utilization. Initiatives such as using advanced technology to monitor and manage the food supply chain, along with awareness campaigns to change consumer behavior, can make a significant difference. These efforts reduce the environmental burden and contribute to global food security. Additionally, the implementation of circular economy principles in industry, where food waste was processed back into useful products, created a more sustainable and efficient system. This is a shared responsibility among governments, industries, and consumers to collaborate in addressing these issues, ensuring a sustainable approach to food waste management.

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