West Science Agro
Vol. 2, No. 03, August 2024, pp. 109~122

Utilisation of Agricultural Wastes as Alternative Raw Materials in Fermented Food Production

Rissa Megavitry[1], Eddy Silamat[2]
[1]Universitas Negeri Makassar
[2]Universitas Pat Petulai

Article Info

Article history:

Received August, 2024
Revised August, 2024
Accepted August, 2024

Keywords:

Agricultural Wastes
Fermented Food Production
Sustainable Food Practices
Waste Valorization
Alternative Raw Materials

ABSTRACT

The increasing demand for sustainable food production has led to a growing interest in the utilization of agricultural wastes as alternative raw materials in the fermentation industry. This systematic literature review examines the potential of agricultural by-products, such as fruit peels, vegetable scraps, and cereal residues, as substrates for fermented food production. By analyzing a wide range of studies, this review identifies the types of agricultural wastes successfully used, the fermentation processes involved, and the benefits derived from these practices, including waste reduction, cost savings, and nutritional enhancement. The review also highlights the challenges associated with the variability in waste composition, logistical constraints, and consumer acceptance. The findings suggest that the utilization of agricultural wastes in fermented food production not only contributes to environmental sustainability but also offers economic and nutritional benefits. However, further research is needed to optimize fermentation processes, assess economic feasibility, and enhance consumer acceptance. This review provides valuable insights for researchers, industry stakeholders, and policymakers interested in promoting sustainable food production practices.

Corresponding Author:

Name: Rissa Megavitry
Institution: Universitas Negeri Makassar
Email: rissamegavitry@unm.ac.id

1. INTRODUCTION

The global food industry is increasingly focusing on sustainable practices, with waste valorisation emerging as a key strategy to address environmental challenges while maintaining productivity. Agricultural waste, traditionally seen as a low-value by-product, is now being recognised for its potential in creating value-added products, particularly in fermented food production. This shift is fuelled by the need to reduce environmental impact and improve resource efficiency within a circular economy framework [1]. Agricultural waste includes various by-products such as fruit peels, vegetable scraps and cereal residues, which are often discarded or used as low-value products such as animal feed or compost [2]. However, advances in bioprocessing technology have shown the potential to recycle these wastes into high nutritional value products. For example, the use of moulds, yeasts and bacteria can improve the nutritional quality of these wastes, making them suitable for animal feed and contributing to a more sustainable food supply system [3]. The conversion of agricultural residues into valuable resources not only addresses environmental degradation but also enhances food security by improving soil health and agricultural yields [4]. This approach is in line with the principles of the circular economy, which emphasises the reuse and recycling of resources to reduce waste and improve economic efficiency [4]. In addition, sustainable waste management practices can reduce negative environmental impacts associated with agricultural production, such as soil degradation and pollution [5]. Despite these advances, challenges remain, including diverse sources of waste, compositional variations, and the need for infrastructure and regulatory frameworks to support efficient waste management [5].

Fermentation is a time-honored process that has been utilized for thousands of years to preserve and enhance the nutritional value of food. It involves the biochemical modification of organic substrates by microorganisms, resulting in a variety of fermented products such as yogurt, sauerkraut, kimchi, and alcoholic beverages. This process not only improves the nutritional profile of foods by increasing the bioavailability of nutrients and synthesizing vitamins but also enhances their shelf life and safety by fostering environments where beneficial microbes outcompete harmful pathogens [6], [7]. The use of agricultural wastes in fermentation aligns with the principles of the circular economy, which emphasizes resource efficiency and waste minimization. By converting low-cost, readily available materials into high-nutrition, marketable food products, fermentation provides a sustainable solution to waste management. This practice is supported by the ability of microorganisms to transform diverse substrates, including cereals, legumes, and vegetables, into valuable fermented foods [6], [7].

Fermentation technology has evolved significantly, with modern techniques such as submerged and solid-state fermentation being employed to optimize the production of both primary and secondary metabolites. These metabolites have applications across various industries, including food, cosmetics, and pharmaceuticals, highlighting the economic potential of fermentation beyond traditional food preservation [8], [9]. Furthermore, the integration of fermentation into food production systems can help address global food scarcity by improving food storage and transportation efficiency, thus securing the future food economy [9]. The dynamic interaction of microbial communities during fermentation not only contributes to the diversity and uniqueness of global culinary traditions but also offers potential health benefits by reducing the allergenic nature of some foods and counteracting antinutritional factors [7].

Despite the promising potential, the utilization of agricultural wastes in fermented food production remains a relatively underexplored area in both academic research and industrial application. The variability in the composition of agricultural wastes, the complexity of fermentation processes, and the need for optimized waste collection and processing systems present significant challenges. Moreover, the economic feasibility and consumer acceptance of such products are critical factors that require further investigation. This systematic literature review aims to consolidate existing knowledge on the utilization of agricultural wastes as alternative raw materials in fermented food production. By analyzing a wide range of studies, this review seeks to identify the types of agricultural wastes that have been successfully used, the specific fermentation processes employed, and the potential benefits and challenges associated with these practices.

2. LITERATURE REVIEW

2.1 Types of Agricultural Wastes Used in Fermentation

Agricultural waste, comprising by-products like fruit peels, vegetable scraps, and cereal residues, is a significant global waste component rich in nutrients such as carbohydrates, proteins, and fibers. These characteristics make them suitable substrates for microbial fermentation, offering a sustainable approach to waste management and resource utilization. The potential of agricultural waste in fermentation processes is well-documented across various studies. Citrus peels, for instance, are high in pectin and have been extensively studied for their use in producing vinegar and bioethanol through fermentation. This aligns with findings that highlight the conversion of lignocellulosic agricultural waste into biofuels, including bioethanol, which can reduce fossil fuel dependence and environmental degradation [10]. Similarly, potato peels and sugar beet pulp, rich in fermentable sugars, have been successfully utilized in producing lactic acid and biogas, supporting the notion that agricultural waste can be a valuable feedstock for biofuel production [10], [11]. Moreover, the use of fruit and vegetable wastes in producing probiotic-rich fermented foods has shown promising results. For example, pineapple peels and mango skins have been used to produce probiotic beverages, retaining high levels of lactic acid bacteria and bioactive compounds, which are beneficial for health [12]. This demonstrates the potential of food waste valorization in creating high-value bioproducts, despite challenges related to feedstock variability [12]. Cereal by-products like wheat bran and rice husks have also been explored for their role in fermenting traditional foods such as tempeh and miso. These by-products provide added nutritional benefits through dietary fibers and essential minerals, further emphasizing the diverse applications of agricultural waste in food production [2].

2.2 Fermentation Processes Involved

The fermentation of agricultural wastes into valuable food products is a multifaceted process that leverages various fermentation techniques, each suited to different types of waste and desired outcomes. Lactic acid fermentation is prominently used for enhancing the nutritional profile of fermented foods like sauerkraut and kimchi by incorporating agricultural wastes such as cabbage leaves and carrot peels. This process not only improves the nutritional value but also adds probiotic benefits, as demonstrated in the fermentation of bakery waste into beverages with high lactic acid bacteria counts and antibacterial properties [13]. Alcoholic fermentation, traditionally used in beverage production, has been adapted to utilize fruit and vegetable wastes, resulting in products with unique flavors and enhanced bioactive properties. This approach aligns with the broader trend of using fermentation to produce food aroma compounds from vegetable waste, offering natural alternatives to chemically synthesized aromas [14]. The fermentation of fruit waste can yield a variety of bioactive compounds, including organic acids and bacterial cellulose, which have significant nutritional and industrial value [15]. Acetic acid fermentation, particularly in the production of vinegar, has shown potential for waste valorization. For instance, apple pomace, a by-product of juice production, can be effectively used to produce apple cider vinegar, demonstrating the feasibility of converting waste into valuable products [16]. Additionally, solid-state fermentation is explored for converting lignocellulosic wastes into enzymes and organic acids, further expanding the scope of waste utilization [17]v. Despite these advancements, challenges remain, particularly in scaling up processes and ensuring consistent quality across different waste types and fermentation conditions. The variability in fermentation rates and outcomes, influenced by factors such as cell wall architecture, highlights the need for tailored approaches to optimize the use of specific agricultural wastes [16].

2.3 Benefits of Using Agricultural Wastes in Fermented Food Production

The utilization of agricultural wastes in fermented food production offers significant environmental, economic, and nutritional benefits. Environmentally, this approach supports waste reduction and promotes a circular economy by transforming by-products into value-added products. For instance, the fermentation of corn gluten meal-bran mixtures not only degrades high molecular weight proteins but also enhances beneficial metabolites such as total phenols and carotenoids, while reducing anti-nutritional factors [18]. Similarly, the fermentation of bread waste into beverages demonstrates the potential for zero-waste production, contributing to sustainable food systems [13]. Economically, using agricultural wastes as substrates in fermentation processes provides a cost-effective alternative to conventional raw materials, thereby reducing production costs. This is exemplified by the fermentation of vegetable waste to produce natural aroma compounds, which can replace chemically synthesized alternatives, meeting consumer demand for "clean label" products [14]. Additionally, the fermentation of fruit waste can yield high-value compounds such as organic acids and bacterial cellulose, further enhancing economic viability [15]. Nutritionally, the incorporation of agricultural wastes into fermented foods can significantly enhance their nutritional profile. Fermentation processes increase the bioavailability of nutrients and produce bioactive compounds, such as probiotics, which contribute to improved health benefits [7]. For example, the fermentation of fruit waste not only valorizes phytochemicals but also converts them into valuable bioactive compounds, enhancing the nutritional value of the final products [15]. Furthermore, fermented products from bread waste exhibit probiotic potential and antibacterial properties, adding functional benefits to the diet [13].

2.4 Challenges in Utilizing Agricultural Wastes

The adoption of agricultural wastes in fermented food production faces several challenges, primarily due to the variability in waste composition, logistical issues, and consumer acceptance. Variability in the composition of agricultural wastes, influenced by factors such as seasonal changes, storage conditions, and agricultural practices, poses significant challenges for standardizing fermentation processes. This variability can affect the nutritional content and microbial load, impacting the consistency and quality of the final product [14], [18]. For instance, the fermentation of vegetable waste for aroma compound production is highly dependent on the specific strains and types of waste used, which can lead to inconsistent results [14]. Logistical challenges also hinder the efficient collection and processing of agricultural wastes. The decentralized nature of agricultural production complicates the gathering and transportation of these materials to fermentation facilities, necessitating efficient waste collection systems [19]. Additionally, pre-treatment processes such as washing, drying, and grinding are often required to prepare substrates for fermentation, adding complexity and cost to the production process [19]. Consumer acceptance is another significant barrier. Despite the nutritional and environmental benefits of fermented foods from agricultural wastes, there is resistance due to concerns about food safety and quality

[5]. Overcoming these barriers requires targeted marketing strategies and educational campaigns to raise awareness about the benefits of these sustainable practices [20]. Research indicates that innovative approaches, such as using specific strains of microorganisms, can enhance the fermentation process and improve product quality. For example, the use of lactic acid bacteria in fermenting bread waste has shown potential in creating sustainable food products with probiotic benefits [13]. Similarly, the fermentation of corn gluten meal-bran mixtures has demonstrated improvements in protein content and beneficial metabolites, suggesting a viable alternative to traditional protein sources in animal husbandry [18].

2.5 Gaps in the Literature and Future Research Directions

While there is a growing body of research on the utilization of agricultural wastes in fermented food production, several gaps remain. Most studies have focused on the technical feasibility of using specific types of waste in fermentation processes, with less attention given to the economic viability and consumer acceptance of these products. Future research should aim to address these gaps by conducting comprehensive cost-benefit analyses and exploring strategies to enhance consumer acceptance.

Additionally, there is a need for further research on the optimization of fermentation processes for different types of agricultural wastes. Developing standardized protocols and identifying key factors that influence the fermentation outcomes will be critical in scaling up these practices for industrial applications. Lastly, exploring the potential of new and underutilized agricultural wastes in fermentation processes could open up new avenues for sustainable food production.

3. METHODS

3.1 Search Strategy

The literature search was conducted in academic databases, including Scopus. These databases were chosen due to their extensive coverage of peer-reviewed journals, conference proceedings, and other scholarly sources. Searches were conducted using a combination of keywords and phrases such as ‘agricultural waste’, ‘fermented food production’, ‘alternative raw materials’, ‘food fermentation’, and ‘waste valorisation’. Boolean operators (AND, OR) were used to refine the search and ensure inclusion of relevant studies.

The search was limited to articles published in English between 1999 and 2024 to focus on recent advances and contemporary research. Additionally, only studies involving the use of agricultural waste in fermented food production were included, excluding studies on non-food fermentation processes or studies that did not mention the type of agricultural waste used.

3.2 Inclusion and Exclusion Criteria

To ensure the relevance and quality of the included studies, specific inclusion and exclusion criteria were applied:

Inclusion criteria for this study included research published in peer-reviewed journals or conference proceedings, specifically targeting research articles, review papers, and case studies exploring the use of agricultural waste in fermented food production. Only studies that provided detailed information on the types of agricultural waste used, the fermentation processes involved, and the outcomes of these processes, as well as those published up to 2024, were considered. Conversely, exclusion criteria ruled out studies that focused on non-food fermentation processes (such as the production of biofuels and industrial enzymes), articles that lacked sufficient details about agricultural waste or fermentation processes, studies published in languages other than English, and studies that were not fully accessible. A total of 29 studies were included in the final criteria of this study.

4. RESULTS AND DISCUSSION

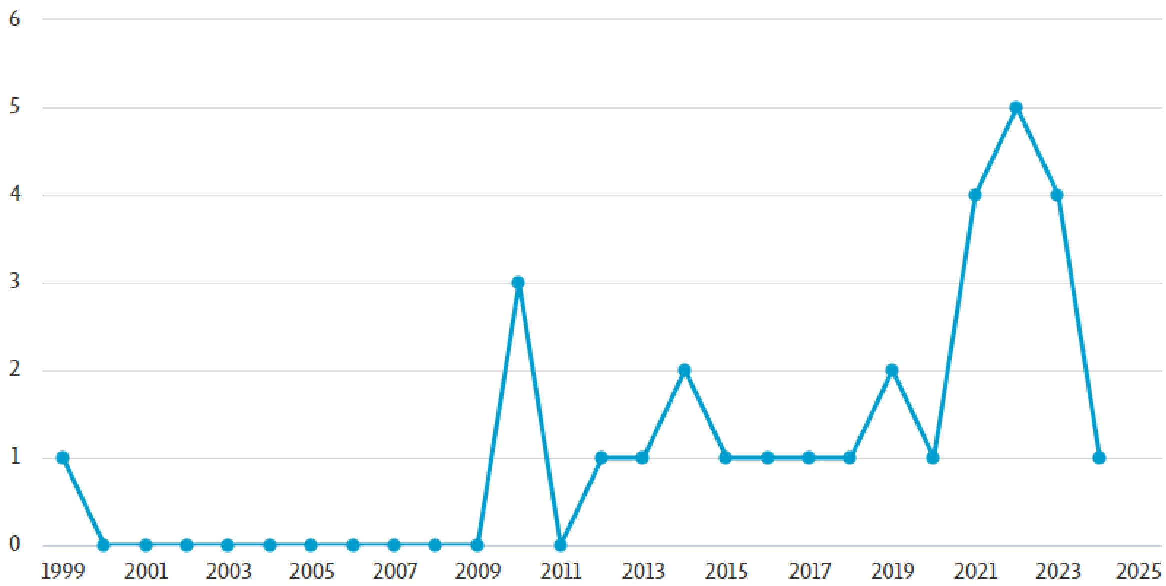

Figure 1. Trend Research

The trend from 1999 to 2008 shows a low and stable level of activity, with only minor fluctuations, suggesting that the topic of interest was not widely explored or recognized in the academic or industrial community during this period. A sudden spike in activity occurs around 2010, indicating a surge in interest, possibly due to a breakthrough study, technological advancement, or emerging relevance of the topic; however, this peak quickly drops back to low levels in the following years, suggesting that the initial interest may have been short-lived. Between 2012 and 2019, there is a gradual increase in activity, with small peaks around 2013 and 2016, reflecting a renewed but cautious interest, likely driven by new research findings, incremental technological improvements, or broader recognition of the topic's importance. From 2020 onward, there is a significant rise in activity, with the highest peak observed around 2021, likely corresponding to a period of heightened relevance due to global events, policy changes, or technological advancements, signaling a significant shift in attention and resources towards this area. However, the trend shows a sharp decline after 2023, indicating that while the topic had peaked in interest, it is now experiencing a downturn, possibly due to the topic reaching a maturity phase or a shift in focus towards newer or adjacent topics.

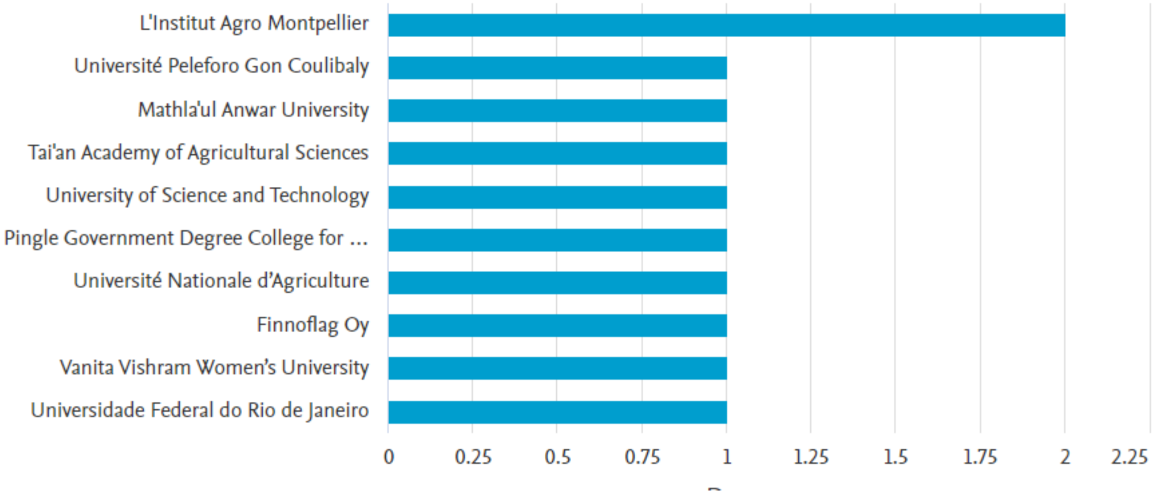

Figure 2. Affiliation

L'Institut Agro Montpellier leads with the highest number of documents, indicating strong activity and expertise in the field. Université Peleforo Gon Coulibaly and Mathla'ul Anwar University follow with document counts close to 1, reflecting significant, albeit lower, contributions. Taian Academy of Agricultural Sciences and University of Science and Technology have similar numbers slightly below 1, indicating active but less central participation. Pingle Government Degree College for Women and Université Nationale d'Agriculture, with counts below 1, indicate moderate involvement, perhaps as newer or smaller players. Finnoflag Oy, Vanita Vishram Women's University, and Universidade Federal do Rio de Janeiro have the lowest counts, slightly above 0.5, indicating either a specialised focus or less extensive output.

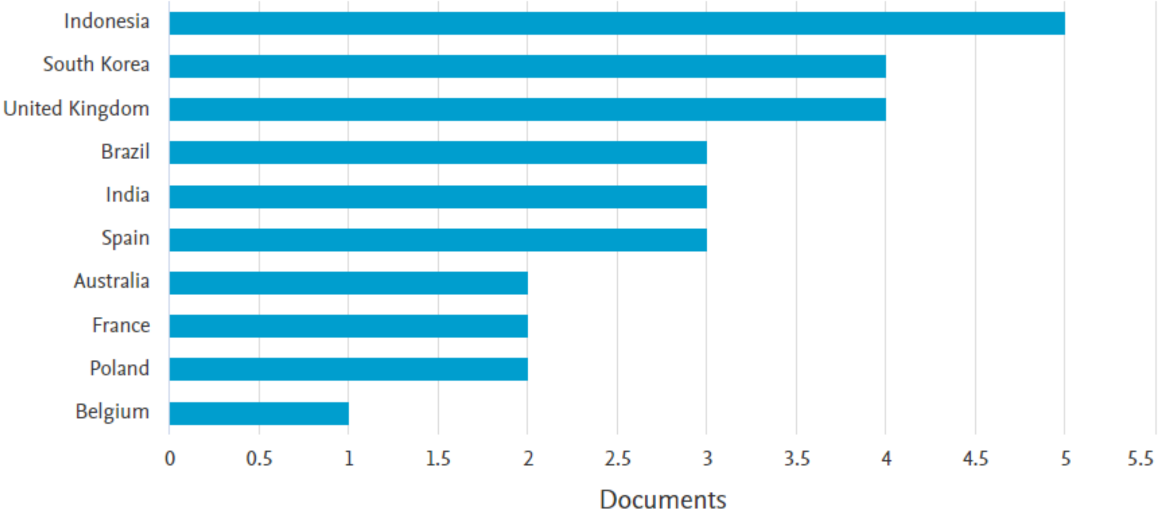

Figure 3. Country Contribution

Indonesia led the way with the highest number of documents, slightly above 5, indicating a strong national focus or urgent local relevance in this area. South Korea and the UK follow close behind with document counts around 4.5, reflecting strong research activities and likely government or institutional support. Brazil, India and Spain, with a document count of around 3.5, are also significant contributors, indicating a shared interest or renewed focus in this area, potentially fuelled by efforts to expand research capacity. Australia, France and Poland, each with around 2, were active but less prominent, perhaps reflecting specialised contributions or focused research efforts. Belgium, with the lowest number below 1, may have a specialised focus or fewer resources dedicated to this research area.

4.1 Types of Agricultural Wastes Utilised

This review identified a diverse range of agricultural wastes that have been explored as substrates for fermentation processes. The utilisation of agricultural wastes, such as fruit peels, vegetable residues and cereal residues, in fermentation processes is supported by their high nutritional content, including fermentable sugars, fibre and essential minerals. These characteristics make them suitable substrates for various fermentation applications. For example, fruit peels such as orange, pineapple, and mango are rich in phytonutrients and bioactive compounds, which have been used effectively in producing bioethanol and probiotic drinks, respectively [21]. The presence of pectin and sugars in citrus peels facilitates their use in vinegar and bioethanol production, while pineapple and mango peels contribute to the fermentation of probiotic drinks, increasing the levels of lactic acid bacteria and bioactive compounds [21]. Cereal by-products, such as wheat bran, are traditionally used in fermentation processes such as tempeh and miso production, where they improve the nutritional profile and texture of the final product [12]. However, the variability in the composition of these agricultural wastes poses challenges for standardisation and consistency in product quality. This variability is mainly due to differences in carbon and nitrogen content, which can affect the efficiency and yield of the fermentation process [12]. Despite these challenges, the potential of agricultural waste in sustainable practices is immense. For example, fruit and vegetable wastes are being explored for their potential in developing biodegradable food packaging materials, which can replace non-degradable petroleum-based plastics [22].

4.2 Fermentation Processes and Yields

The literature highlights several fermentation processes used in converting agricultural waste into fermented foods, with lactic acid fermentation, alcoholic fermentation, and acetic acid fermentation being the most common.

Lactic acid fermentation is a well-established process in the production of vegetable-based fermented foods, such as sauerkraut and kimchi, and is recognised to improve the nutritional profile of these products. The incorporation of vegetable waste, such as cabbage leaves and carrot peels, into the fermentation process can further enhance the nutritional value by retaining dietary fibre, vitamins and bioactive compounds, which contribute to the health benefits of these foods. Research shows that lactic acid bacteria (LAB) play an important role in this process by utilising the nutrients and active compounds present in the plant-based ingredients. The metabolic pathways and enzyme systems of LAB improve the nutritional and functional properties of fermented products, making them more nutritious and palatable [23]. The fermentation process not only improves organoleptic properties, such as flavour and texture, but also increases the bioavailability of vitamins and minerals, enriches the phenolic profile and bioactivity components of the product [24]. Moreover, controlled fermentation with selected LAB strains can ensure high-quality products with superior nutritional and organoleptic properties. This approach is particularly beneficial for incorporating non-traditional vegetables and by-products, thus promoting sustainability and reducing waste [25]. The use of LAB fermentation starters can also inhibit pathogenic bacteria, improve flavour, and reduce harmful substances such as nitrites, further improving the safety and shelf-life of fermented vegetables [26]. In addition, fermentation of vegetable matrices, including legumes, has shown potential to improve texture and remove unwanted flavours, while some LAB strains can produce carotenoids, adding nutritional value to the product [27].

Alcoholic fermentation is an important process in the production of alcoholic beverages, such as cider and wine, and involves the conversion of sugar into alcohol and other compounds by yeast, mainly Saccharomyces cerevisiae [28]. The use of fruit wastes, such as apple pomace and grape skins, in alcoholic fermentation not only produces fermentable sugars, but also improves the sensory and nutritional quality of the resulting beverages. Research shows that fruit waste can significantly contribute to the flavour and aroma profile of alcoholic beverages. The metabolic activity of yeast during fermentation produces various volatile compounds, which, together with the inherent volatile components of the fruit waste, play an important role in determining the final sensory properties of the beverage [29]. These volatile compounds include esters, terpenes, and aldehydes, which are important for the aroma and flavour of the final product [28], [29]. In addition, fermentation of fruit by-products can increase the antioxidant capacity of the resulting beverages. This is due to the conversion of phytochemicals present in the fruit waste into bioactive compounds during fermentation, which can increase the nutritional value of the beverage [15], [30]. Antioxidant activity is particularly beneficial as it can contribute to the health-enhancing properties of the beverage, making it more appealing to health-conscious consumers [30]. The utilisation of apple pomace in fermentation processes has been studied for its potential to regulate ethanol production and improve fermentation quality. Adjusting moisture levels and using specific lactic acid bacteria can optimise fermentation conditions, although these methods mainly target feed production rather than beverage production [31].

Acetic acid fermentation, a key process in vinegar production, has shown significant potential in utilising fruit waste, such as apple peels and citrus peels, to produce high-quality vinegar with a rich volatile compound profile. The process involves the oxidative fermentation of alcohols by acetic acid bacteria, which can be isolated from traditionally fermented vinegar and optimised for specific substrates [32], [33]. Research has shown that various fruit wastes can be effectively converted into vinegar. For example, the use of unripe Citrus unshiu and other fruit wastes such as citrus and sugarcane has been explored, with promising results in terms of acidity and volatile compound production. The acetic acid bacterium Komagataeibacter kakiaceti P6, which was isolated for its superior acetic acid production, achieved a total acidity of 4.86% in raw unshiu citrus vinegar, indicating its potential for high-efficiency fermentation [32]. Similarly, vinegars produced from fruit wastes such as citrus and sugarcane show increased titratable acidity, ranging from 6.6% to 7.7%, and a profile rich in volatile compounds, which enhances the sensory attributes of the final product [33]. The fermentation process not only increases the acidity but also enriches the vinegar with phenolic compounds and flavonoids, which contribute to its antioxidant properties. For example, fermentation of mangosteen vinegar resulted in increased levels of phenolic and flavonoid content, indicating additional health benefits [34]. In addition, the use of immobilised fermentation techniques with carrier materials such as rice husks has been shown to improve aroma and acid production efficiency, further enhancing vinegar quality.

4.3 Benefits of Utilising Agricultural Waste

Utilisation of agricultural waste in fermented food production offers many benefits, which can be categorised into environmental, economic and nutritional advantages.

The environmental benefits of diverting agricultural waste from landfills and reusing it as feedstock for fermentation are aligned with the principles of the circular economy, where waste is viewed as a resource rather than a burden. This approach significantly contributes to waste reduction and environmental sustainability. Firstly, the reduction of avoidable consumer food waste (ACFW) can result in substantial environmental benefits, such as reduced emissions, water use, and land use. A 50% reduction in ACFW can save up to 198 Mt CO2eq of emissions and 30 Gm3 of blue water, highlighting the potential of waste reduction in reducing environmental impacts

[35]. Similarly, the production of bioplastics from food waste offers a sustainable alternative to fossil-based plastics, reducing climate change, eutrophication, and ecotoxicity, although energy consumption remains a challenge [36]. Moreover, the integration of waste into the production chain through innovative biorefineries, as demonstrated by model 2IB, shows significant environmental advantages compared to traditional landfill methods. This model results in lower global warming potential and reduced resource depletion, supporting the circular economy framework [37]. In addition, a study on delivered food waste in Jiuquan, China, emphasised the importance of waste prevention and reduction at the upstream stage, which is more beneficial than managing waste at the final stage [38]. A holistic examination of the food supply chain further underscores the need for sustainable practices to reduce carbon emissions and align production with demand, thereby minimising waste [39].

Using agricultural waste as an alternative feedstock in fermented food production offers significant economic benefits, especially in resource-constrained environments. Agricultural residues, which are often underutilised, present a cost-effective alternative to conventional feedstocks due to their low or negligible cost. This can substantially reduce production costs and increase profitability in the fermentation industry. The transformation of agricultural waste into bio-alcohol and other value-added products supports the circular economy by reusing waste as a resource, thereby reducing the need for new feedstock and minimising waste management costs [40], [41]. This approach not only lowers production costs but also contributes to environmental sustainability by reducing greenhouse gas emissions associated with waste combustion [41], [42]. In addition, the conversion of agricultural waste into biofuels and derivatives can fulfil the demand for energy and chemicals, further increasing the economic potential of these materials [42]. Biofuel production from agricultural waste, for example, can be a sustainable energy source that reduces dependence on fossil fuels, thus offering additional economic benefits such as energy security and foreign exchange savings [40]. In addition, the fermentation of agricultural waste into products such as Agricultural Jiaosu (AJ) shows potential for creating environmentally friendly and sustainable products. This process not only utilises waste effectively but also produces valuable metabolites and supports microbial diversity, which can be tailored to specific applications, further enhancing economic viability [32].

Fermented foods produced from agricultural waste offer significant nutritional benefits, mainly due to the retention and enhancement of bioactive compounds, fibre and nutrients present in the original waste material. The fermentation process not only retains these nutrients, but also increases bioavailability and introduces probiotics, which are beneficial to gut health. Research shows that fermentation improves the nutritional value and quality of food by facilitating microbial growth and enzymatic conversion, which increases the bioavailability of vitamins and minerals [43]. This process enriches the phenolic profile and bioactivity components of foods, resulting in functional foods with improved health benefits [24]. The presence of probiotics in fermented foods contributes to health and nutrition by promoting the growth of beneficial bacteria in the gut and protecting the survival of probiotics in the gastrointestinal tract [6]. In addition, fermentation can lead to vitamin synthesis and the production of bioactive compounds, further improving the nutritional profile of foods [6]. This biotechnological process also helps to reduce the allergenic properties of some foods and counteract antinutritional factors, thereby improving digestibility and safety [6]v. The dynamic interaction of microbial communities during fermentation not only extends the shelf life of foods but also ensures their microbiological safety [6]. In addition, fermentation of fruit and vegetable juices has been shown to improve their organoleptic properties and shelf-life, making it a viable option for the utilisation of high-quality agricultural waste [24]. This approach is in line with the growing interest in fermentation technologies to value food waste into valuable by-products, contributing to sustainable food security [6].

4.4 Challenges and Limitations

Despite their benefits, several challenges and limitations hinder the widespread adoption of agricultural wastes in fermented food production.

Variability in the composition of agricultural wastes is a significant challenge in their use for fermentation processes. Factors such as crop type, growing conditions, and post-harvest handling contribute to inconsistencies in nutrient content and microbial load, which affect the fermentation process and quality of the final product. Variability in carbon and nitrogen content, as well as specific substrates in food waste hydrolysates, limit their use for bioproduct synthesis, as shown in studies focussing on the production of polyhydroxyalkanoates and sophorolipids [12]v. Overcoming this variability requires strategies such as media standardisation and the use of non-selective microbial organisms to improve industrial-scale valorisation [12]. Logistical challenges in the collection, storage and transport of agricultural waste are exacerbated in decentralised agricultural regions. Efficient systems are required to manage these processes, including pre-treatment steps such as washing, drying, and grinding, which add complexity and cost [44]. Effective waste management practices, such as composting and anaerobic digestion, can turn waste into a valuable resource, but require infrastructure development and policy support [45]. Consumer acceptance of fermented foods made from agricultural waste is another hurdle. Despite the environmental and nutritional benefits, there may be resistance due to perceptions about food safety and quality. Addressing this issue through education and marketing strategies is crucial. The marketing mix, including distribution and pricing strategies, can influence consumer behaviour and reduce waste [46]. In addition, facilitating connectivity and information sharing among supply chain members can improve waste management efficiency and promote a circular economy [47].

4.5 Future Directions

This review identified several areas for future research and development to address the challenges associated with the use of agricultural waste in fermented food production.

Future research should focus on optimising fermentation conditions for different types of agricultural waste. This includes developing standardised protocols that account for variability in waste composition and ensure consistent product quality.

A comprehensive cost-benefit analysis is needed to assess the economic feasibility of using agricultural waste in fermented food production. The study should consider the costs of waste collection, treatment, and fermentation, as well as the potential market value of the final product.

To increase consumer acceptance, targeted educational campaigns are needed to inform the public about the benefits of fermented foods made from agricultural waste. Marketing strategies should emphasise the nutritional and environmental advantages of these products, positioning them as sustainable and health-conscious options.

There is also a need to explore the potential of underutilised agricultural wastes in fermentation processes. Research in this area could discover new substrates with unique nutritional and functional properties, which could further expand the range of fermented foods available in the market.

5. CONCLUSION

This systematic literature review has provided a comprehensive overview of the utilization of agricultural wastes as alternative raw materials in fermented food production. The findings highlight the significant potential of agricultural by-products, such as fruit peels, vegetable scraps, and cereal residues, to serve as valuable substrates for various fermentation processes. These practices contribute to environmental sustainability by reducing waste and promoting a circular economy. Economically, the use of low-cost or no-cost agricultural wastes offers a cost-effective alternative to conventional raw materials, potentially increasing the profitability of fermented food production.

Nutritionally, the incorporation of agricultural wastes into fermented foods enhances the bioavailability of nutrients and introduces beneficial probiotics, offering improved health benefits to consumers. Despite these advantages, several challenges must be addressed to fully realize the potential of agricultural waste utilization in fermentation. Variability in waste composition, logistical challenges in waste collection and processing, and consumer acceptance remain significant barriers.

Future research should focus on optimizing fermentation processes to account for the variability in waste composition and ensure consistent product quality. Comprehensive economic feasibility studies are also needed to evaluate the cost-effectiveness of using agricultural wastes on a larger scale. Additionally, targeted consumer education and marketing strategies will be crucial in promoting the acceptance of fermented foods made from agricultural wastes.

REFERENCES

[1] V. Sharma, A. Singh, M. Grenier, V. Singh, and M. Thakur, “Waste Valorization in Food Industries: A Review of Sustainable Approaches,” *Sustain. Food Syst. (Volume II) SFS Nov. Sustain. Green Technol. Circ. Strateg. Food Saf. Divers.*, pp. 161–183, 2023.

[2] B. Koul, M. Yakoob, and M. P. Shah, “Agricultural waste management strategies for environmental sustainability,” *Environ. Res.*, vol. 206, p. 112285, 2022.

[3] X. Sun, Z. Dou, G. C. Shurson, and B. Hu, “Bioprocessing to upcycle agro-industrial and food wastes into high-nutritional value animal feed for sustainable food and agriculture systems,” *Resour. Conserv. Recycl.*, vol. 201, p. 107325, 2024.

[4] A. Sheer *et al.*, “Trends and social aspects in the management and conversion of agricultural residues into valuable resources: A comprehensive approach to counter environmental degradation, food security, and climate change,” *Bioresour. Technol.*, p. 130258, 2023.

[5] R. Phiri, S. M. Rangappa, and S. Siengchin, “Agro-waste for renewable and sustainable green production: A review,” *J. Clean. Prod.*, p. 139989, 2023.

[6] S. A. Siddiqui *et al.*, “An overview of fermentation in the food industry-looking back from a new perspective,” *Bioresour. Bioprocess.*, vol. 10, no. 1, p. 85, 2023.

[7] V. K. Joshi and A. Pandey, “Food fermentation,” *Biotechnol. Asiotech Publ. Inc*, 1999.

[8] S. A. Siddiqui, D. Lakshmikanth, C. Pradhan, Z. Farajinejad, R. Castro-Muñoz, and A. Sasidharan, “Implementing fermentation technology for comprehensive valorisation of seafood processing by-products: A critical review on recovering valuable nutrients and enhancing utilisation,” *Crit. Rev. Food Sci. Nutr.*, pp. 1–28, 2023.

[9] O. Krotova, O. Tyulumdjieva, N. Vertiy, A. Ushakov, N. Isaeva, and V. Lodyanov, “Fermentation biotechnology applied to byproducts of the fish processing industry: Nutrition and functionality information,” in *BIO Web of Conferences*, EDP Sciences, 2024, p. 3006.

[10] M. Zielińska and K. Bułkowska, “Agricultural Wastes and Their By-Products for the Energy Market,” *Energies*, vol. 17, no. 9, p. 2099, 2024.

[11] A. Khaswal, S. K. Mishra, N. Chaturvedi, S. Saini, B. Pletschke, and R. C. Kuhad, “Microbial enzyme production: Unlocking the potential of agricultural and food waste through solid-state fermentation,” *Bioresour. Technol. Reports*, p. 101880, 2024.

[12] P. Wongsirichot *et al.*, “Food wastes for bioproduct production and potential strategies for high feedstock variability,” *Waste Manag.*, vol. 184, pp. 1–9, 2024.

[13] K. Juś, M. Ścigaj, D. Gwiazdowska, K. Marchwińska, and W. Studenna, “Innovative Fermented Beverages Based on Bread Waste—Fermentation Parameters and Antibacterial Properties,” *Appl. Sci.*, vol. 14, no. 12, p. 5036, 2024.

[14] F. Melini and V. Melini, “Role of Microbial Fermentation in the Bio-Production of Food Aroma Compounds from Vegetable Waste,” *Fermentation*, vol. 10, no. 3, p. 132, 2024.

[15] D. R. A. Muhammad, V. B. Nguyen, P. H. Le, and A. P. Sanjaya, “Microbial metabolites and bioactive compounds from fermented fruit waste,” in *Bioactive Microbial Metabolites*, Elsevier, 2024, pp. 83–121.

[16] B. M. Flanagan, B. A. Williams, F. Sonni, D. Mikkelsen, and M. J. Gidley, “In vitro fermentation characteristics of fruit and vegetable juicing wastes using human fecal inoculum are determined by cell wall architecture,” *Food Hydrocoll.*, vol. 146, p. 109205, 2024.

[17] B. Chatterjee and D. Mazumder, “A critical review of the advances in valorizing agro-industrial wastes through mixed

culture fermentation," *J. Environ. Chem. Eng.*, p. 111838, 2023.

[18] S. Zhang, Q. Li, Z. Huang, G. Wang, X. Zheng, and J. Liu, "Exploring community succession and metabolic changes in corn gluten meal-bran mixed wastes during fermentation," *J. Environ. Manage.*, vol. 366, p. 121684, 2024.

[19] R. A. Dar *et al.*, "Fermentation of organic wastes through oleaginous microorganisms for lipid production-Challenges and opportunities," *Renew. Sustain. Energy Rev.*, vol. 195, p. 114328, 2024.

[20] V. K. Aggarwal and R. Aggarwal, "On Inspecting the Hierarchical Inter-Relationships amongst the Various Barriers to Successful Adoption of Various Fermented Food Products," 2024.

[21] M. Wanapat *et al.*, "The recycling of tropical fruit peel waste-products applied in feed additive for ruminants: food manufacturing industries, phytonutrient properties, mechanisms, and future applications," *J. Agric. Food Res.*, p. 101234, 2024.

[22] A. Y. Yildiz and S. Öztekin, "Utilization of Fruit and Vegetable Wastes in Food Packaging," *Agro-Wastes Packag. Appl.*, p. 197, 2024.

[23] X. Yang *et al.*, "Effect of Lactic Acid Bacteria Fermentation on Plant-Based Products," *Fermentation*, vol. 10, no. 1, p. 48, 2024.

[24] S. Saud, T. Xiaojuan, and S. Fahad, "The consequences of fermentation metabolism on the qualitative qualities and biological activity of fermented fruit and vegetable juices," *Food Chem. X*, p. 101209, 2024.

[25] R. S. Aleman, I. Montero-Fernández, J. A. Marcía, S. A. Saravia Maldonado, and D. Martín-Vertedor, "Application of fermentation as a strategy for the transformation and valorization of vegetable matrices," *Fermentation*, vol. 10, no. 3, p. 124, 2024.

[26] Y. Lu *et al.*, "Fermented vegetables in China: overview, novel processes, influencing factors, lactic acid bacteria and industrialisation status," *Int. J. Food Sci. Technol.*, vol. 59, no. 7, pp. 4420–4436, 2024.

[27] R. Fernández-Varela *et al.*, "Harnessing Fermentation by Bacillus and Lactic Acid Bacteria for Enhanced Texture, Flavor, and Nutritional Value in Plant-Based Matrices," *Fermentation*, vol. 10, no. 8, p. 411, 2024.

[28] M. H. Shahrajabian and W. Sun, "Study of Different Types of Fermentation in Wine-Making Process and Considering Aromatic Substances and Organic Acid.," *Curr. Org. Synth.*, 2023.

[29] D. Stanzer, K. Hanousek Čiča, M. Blesić, M. Smajić Murtić, J. Mrvčić, and N. Spaho, "Alcoholic fermentation as a source of congeners in fruit spirits," *Foods*, vol. 12, no. 10, p. 1951, 2023.

[30] E. Erskine, G. Ozkan, B. Lu, and E. Capanoglu, "Effects of fermentation process on the antioxidant capacity of fruit byproducts," *ACS omega*, vol. 8, no. 5, pp. 4543–4553, 2023.

[31] J. Fang, Z. Du, and Y. Cai, "Fermentation Regulation and Ethanol Production of Total Mixed Ration Containing Apple Pomace," *Fermentation*, vol. 9, no. 7, p. 692, 2023.

[32] Y. Gao *et al.*, "An innovative way to treat cash crop wastes: the fermentation characteristics and functional microbial community using different substrates to produce agricultural Jiaosu," *Environ. Res.*, vol. 227, p. 115727, 2023.

[33] S. K. Paul, J. R. Wartu, and A. A. Orukotan, "Production of vinegar from waste fruits using Acetobacter species," *Ife J. Sci.*, vol. 26, no. 1, pp. 179–200, 2024.

[34] N. Saelee, L.-Z. Cheong, and M. Chaijan, "Optimized Acetic Acid Production by Mixed Culture of Saccharomyces cerevisiae TISTR 5279 and Gluconobacter oxydans TBRC 4013 for Mangosteen Vinegar Fermentation Using Taguchi Design and Its Physicochemical Properties," *Foods*, vol. 12, no. 17, p. 3256, 2023.

[35] A. Coudard, Z. Sun, P. Behrens, and J. M. Mogollón, "The Global Environmental Benefits of Halving Avoidable Consumer Food Waste," *Environ. Sci. Technol.*, 2024.

[36] K. Synani, K. Abeliotis, K. Velonia, A. Maragkaki, T. Manios, and K. Lasaridi, "Environmental Impact and Sustainability of Bioplastic Production from Food Waste," *Sustainability*, vol. 16, no. 13, p. 5529, 2024.

[37] A. P. Clasen, F. Agostinho, C. M. V. B. Almeida, G. Liu, and B. F. Giannetti, "Advancing towards circular economy: Environmental benefits of an innovative biorefinery for municipal solid waste management," *Sustain. Prod. Consum.*, vol. 46, pp. 571–581, 2024.

[38] C. Sun and H. Zhang, "Characterization, environmental impact and reduction strategies for the delivery food waste generated by urban and township residents in Jiuquan, China," *Waste Manag.*, vol. 174, pp. 371–381, 2024.

[39] N. R. Ema, M. A. H. Mithu, and A. Sayem, "Unveiling opportunities for environmental waste reduction and sustainable food production in the supply chain: a holistic examination of key areas," 2024.

[40] D. Borah, B. Edachery, J. Rout, and T. Nooruddin, "Production and Characterization of Bio-alcohols from Agricultural Wastes," in *Emerging Trends and Techniques in Biofuel Production from Agricultural Waste*, Springer, 2024, pp. 147–174.

[41] Z. Y. Serçinoğlu, "Bioprocessing of Agricultural and Agro-Industrial Wastes into Value-Added Products," *Yuz. Yıl Univ. J. Agric. Sci.*, vol. 33, no. 4, pp. 729–741.

[42] Y. M. Espinoza-Vázquez, N. V. Hernández-Camacho, and F. I. Gómez-Castro, "Agricultural Residues as Raw Materials for a Bio-based Industry," in *Sustainable Agricultural Practices and Product Design*, ACS Publications, 2023, pp. 77–99.

[43] S. Paramithiotis, J. K. Patra, Y. Kotseridis, and M. Dimopoulou, "Fermented beverages revisited: From terroir to customized functional products," *Fermentation*, vol. 10, no. 1, p. 57, 2024.

[44] R. Kumar, A. Kaur, S. Sharma, H. Bharti, and R. Kumar, "Advancements And Challenges In Agriculture Waste Management: A Comprehensive," *Educ. Adm. Theory Pract.*, vol. 30, no. 5, pp. 7253–7273, 2024.

[45] S. Periyasamy *et al.*, "Influencing factors and environmental feasibility analysis of agricultural waste preprocessing routes towards biofuel production–A review," *Biomass and Bioenergy*, vol. 180, p. 107001, 2024.

[46] M. Mahmoudi, H. Mohammadi, S. Saghaian, and A. Karbasi, "Factors Affecting the Waste of Selected Agricultural Products with an Emphasis on the Marketing Mix," *Agriculture*, vol. 14, no. 6, p. 857, 2024.

[47] Q. Zhang and H. Zhang, "Assessing Agri-Food Waste Valorization Challenges and Solutions Considering Smart Technologies: An Integrated Fermatean Fuzzy Multi-Criteria Decision-Making Approach," *Sustainability*, vol. 16, no. 14, p. 6169, 2024.