



International Journal of Agriculture and Food Science

ISSN Print: 2664-844X
 ISSN Online: 2664-8458
 NAAS Rating (2026): 4.97
 IJAFS 2026; 8(4): 248-257
www.agriculturaljournals.com
 Received: 02-01-2026
 Accepted: 05-02-2026

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Agricultural waste as food, feed and functional products

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DOI: <https://www.doi.org/10.33545/2664844X.2026.v8.i4d.1315>

Abstract

Agricultural and agro-industrial activities generate substantial quantities of residues, including husks, peels, bagasse, pomace, and animal by-products. These materials are often treated as waste and disposed of through inefficient or environmentally harmful practices, resulting in the loss of valuable nutrients and bioactive compounds. However, these residues are rich sources of dietary fiber, proteins, phytochemicals, and other functional biomolecules that can be effectively converted into value-added food, feed, and functional products. This review provides a comprehensive overview of current approaches for the valorization of agricultural and agro-industrial wastes, with particular emphasis on applications in food and animal feed systems. Both conventional and emerging extraction technologies are discussed, including enzyme-assisted extraction, ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction. These techniques demonstrate significant potential for recovering high-value compounds from low-cost raw materials. In addition, recent advancements such as encapsulation, nanoemulsion systems, and fermentation-based strategies are highlighted for improving the stability and bioavailability of recovered bioactives. The utilization of agro-residues in animal feed production, particularly through solid-state fermentation, is also discussed as a sustainable approach to enhance protein content and reduce anti-nutritional factors. The review further addresses key challenges, including raw material collection, process scalability, economic feasibility, and consumer acceptance. Future prospects are explored with an emphasis on integrated biorefinery approaches and supportive policy frameworks. Overall, this review underscores the potential of agricultural waste valorization in promoting sustainable food systems, reducing environmental impact, and improving resource efficiency.

Keywords: Agricultural waste valorization, agro-industrial by-products, solid-state fermentation, animal feed

Introduction

The main driver of the world economy, agriculture provides the basis for industrial growth, energy production, and food security. But it is also the main cause of environmental stress, waste, and greenhouse gas emissions. With an estimated nearly 1.33 billion metric tonnes of waste produced yearly, including over 1.12 billion metric tonnes from industrial activity, Canada, for instance, has been said to produce the most rubbish globally. Around 4532 trillion British thermal units (TBtu) of biomass were produced in the US in 2020, which accounted for 4.9% of all primary energy use. Of this, 430 TBtu came from biomass derived from municipal trash, 2000 TBtu from biofuels, and 2101 TBtu from wood and biomass obtained from wood. Germany is the top producer of biofuel in Europe, whereas the Indonesia, Brazil, and United States are among the top producers worldwide ^[1]. These figures demonstrate the scope of agricultural production as well as the major obstacles associated with resource use and waste management. While the portion of crop which is not consumable, like peels, shells, stalks, husks, and press cakes, are classified as agricultural wastes, the consumable fractions of crops provide humans with direct supplies of nutrition and energy. These leftovers are produced in enormous amounts and frequently have significant levels of biological oxygen demand (BOD), suspended solids and chemical oxygen demand (COD). In addition to polluting soil and water, improper disposal practices like open dumping, uncontrolled landfilling, and burning also significantly increase greenhouse gas emissions ^[2]. The most of agricultural and agro-industrial wastes are still underutilized despite their abundance, which damages the environment and costs money.

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Agro-industrial residues are rich sources of nutrients, dietary fibers, bioactive compounds, and functional biomolecules, which can be converted into wide range of value-added products. These materials find potential applications across several sectors, including environmental remediation, food, feed, energy, and pharmaceuticals. Research has demonstrated diverse uses of agricultural wastes such as biofuel production^[3], synthesis of nanomaterials^[4], removal of dyes and heavy metals from wastewater^[5], development of bioconstruction materials^[6], and production of bio-alcohols^[7]. Despite these promising applications, many of these inventions remain scattered and underexploited, highlighting the vast untapped potential of waste valorization. In this context, the present review aims to provide a comprehensive overview of the conversion of agricultural wastes into useful products, with particular focus on food, feed and functional application. It brings together existing knowledge, discuss technology approaches for waste transformation, and examines selected case studies that illustrate practical pathways toward sustainable and efficient utilization. The review aims to further the conversation on sustainable agriculture, the circular bioeconomy, and the creation of value-added goods that benefit society and the environment by highlighting the potential of agro-residues as renewable resources.

Food waste and loss are urgent worldwide problems that have significant results on environment, the economy, and the society. Annually, around 1.3 billion tons of food roughly one-third of the world's production are lost or wasted, using up nearly 30% of agricultural area and significantly increasing greenhouse gas emissions. Wastage of food happens at the levels of consumer and retailers and is mostly caused by lifestyle decisions and purchasing habits, whereas food that has gone bad is described as a decline in the quality and amount of food throughout production, postharvest handling, and processing^[8]. Each region generates waste at a different scale and stage. While developing nations frequently suffer losses at early supply chain stages due to inadequate facilities, countries with high-income, such those in Europe and North America, generate more waste at the consumer stage (175–200 kg per capita year)^[9]. Approximately 931 million tons of food waste were reported worldwide in 2019, with the largest contributors being households (61%), food services (26%), and retail (13%)^[10]. Animal-derived by-products (manure, offal, dairy whey), crop residues (stalks, straw, bagasse, culls), and processing wastes (peels, pomace, bran, seeds, pulp) are all examples of agricultural and food wastes^[11, 12, 13]. Therefore, the expansion of resource efficiency, value

added food products, and the circular economy all depend on the valorization of agricultural waste.

Important by products

Agricultural waste includes crop remains, animal corpses, plastic trash, fertilizer and pesticide runoff, agro-industrial waste, crop residues, livestock waste, and food waste. Agricultural waste is produced by a variety of farming operations and must be appropriately managed to lessen its adverse environmental consequences. Recently, agro-industrial residues from root crops and food-processing industries have drawn attention because of their rich organic matter and suitability for microbial valorisation^[14]. Wheat straws are the dry stem that remains after wheat grain is harvested is known as wheat straw. The husk of rice is the insulating outer layer of rice grains that is destroyed during milling. The milling process produces rice husks, which build up in significant amounts in rice-producing areas. Sugarcane bagasse which is fibrous waste left after sugarcane juice is extracted. In regions where sugarcane is processed, bagasse which is created during the sugar extraction process is commonly accessible. Organic waste like leaves are produced by the natural shedding or harvesting of plant leaves. In gardening and farming, leaf debris often builds up in specific seasons, such the fall. Recent studies highlight that fruits, vegetables, and root crops account for nearly half of global food waste and are especially rich in carbohydrates, cellulose, soluble sugars, and organic acids, making them highly suitable substrates for microbial bioprocessing.

Other wastes like cassava processing generates significant residues, particularly cassava wastewater (manihot wastewater), which contains high organic loads and requires careful management due to the presence of toxic compounds such as cyanide. Consequently, stringent treatment is necessary before its discharge into the environment^[15, 16, 17]. Owing to their high carbohydrate content, these residues are increasingly being explored as promising substrates for microbial fermentation processes^[18]. Orange peel is a particularly valuable agro-industrial residue, as it contains proteins, carbohydrates, lipids, lignin, polyphenols, and natural pigments, which enable its conversion into value-added products such as bioplastics, functional polymers, organic acids, and various microbial metabolites.^[19] Orange peel has been used as the sole carbon source for the cultivation of *Aspergillus niger*, resulting in the production of 558 mg/mL of xylo-oligosaccharides under optimized fermentation conditions, thereby demonstrating its potential as a carbohydrate-rich substrate^[20].

Table 1: Economic, nutritional, and environmental impacts of food waste

Aspect	Key Impacts	Statistics	References
Nutritional	Loss of macronutrients, micronutrients, and bioactives	Annual waste could feed 2 billion people at 2,100 kcal/day; U.S. waste = 33 g protein & 1,217 kcal/person/day	[21, 10, 22, 23]
Environmental	GHG emissions, water/energy footprint, pollution	~3.3 billion tons CO ₂ annually; landfill = 43% energy loss; 16 kg waste in China = +40 kg CO ₂ eq	[9, 24, 25, 26]
Economic	Financial losses from wasted production and disposal	Global cost ~USD 1 trillion (up to 2.6 trillion incl. externalities); U.S. = USD 198 billion; U.K. = USD 18.6 billion	[27, 28, 29, 30]

An organized summary of the losses in the form of important agro wastes, their key impacts is shown in Table 1. Recent studies indicate that fruits, vegetables, and root crop residues account for nearly half of global food waste and are rich in carbohydrates, cellulose, soluble sugars, minerals,

and organic acids, making them highly suitable substrates for bioprocessing applications^[33]. Interestingly, non-edible fractions such as peels and seeds often contain higher concentrations of bioactive compounds than the edible portions, highlighting the need for systematic compositional

evaluation prior to their utilization [34, 35]. Therefore, compounds like nutraceuticals, bioactives, antioxidants, polysaccharides, biopolymers, single cell proteins, biopeptides, antibiotics, industrial enzymes, bionanocomposites, activated carbon, chitosan, organic acids, pigments, sugars, and xanthan gum are few of the high-value compounds that can be recovered from byproducts and food wastes [31, 32]. In addition, the biorefinery approach are widely applied to citrus waste streams to identify optimal valorization pathways such as the production of pectin, xylo-oligosaccharides, and organic

acids based on raw material availability, seasonal variation, and overall process sustainability [36]. The replacement of chemicals, fuels, and materials derived from fossil fuels depends on the sustainable use of renewable resources. Green chemical and biotechnological methods, such as cascade processing of agricultural, forestry, and aquatic biomass, integrated biorefining, industrial symbiosis, and specialty product extraction, are used can be used accomplish this [37, 38]. The concept is diagrammatically shown in Figure 1 depicting the valorisation pathways of agricultural and food wastes."

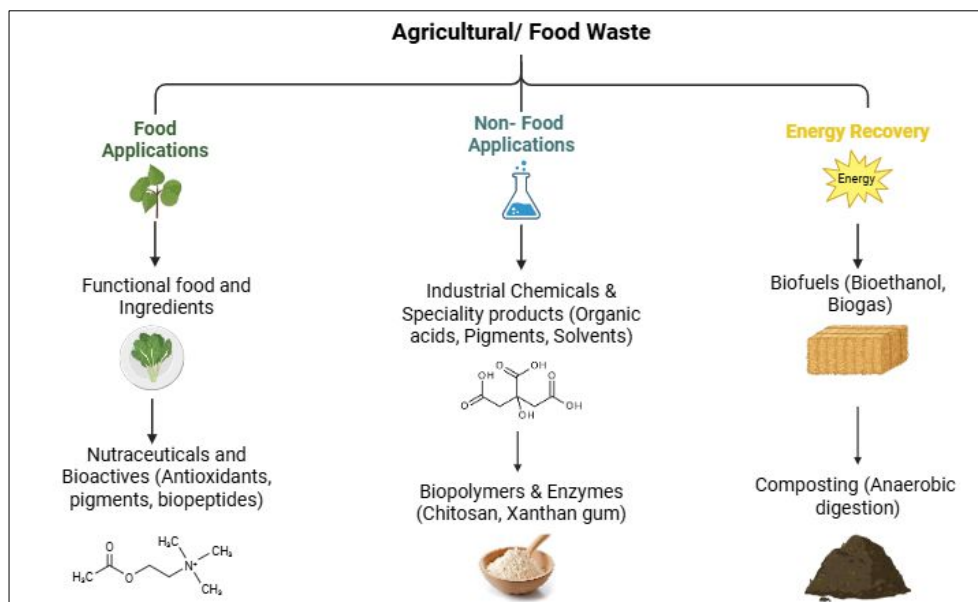


Fig 1: Valorisation Pathways of Agricultural and Food Wastes

Techniques used for extraction of valuable substances from by products

Instead of being produced from petroleum-based chemicals, biobased compounds, phytochemicals, and natural biopolymers can be recovered directly through extraction from agricultural and food wastes [39]. These priceless substances can be categorized as high-value goods and used as nutraceuticals, cosmetics, medicines, and food additives [40]. In order to fully exploit the byproducts, efficient valorization necessitates choosing extraction techniques that optimize recovery while reducing waste [38]. The characteristics of the food matrix and the target bioactive chemicals have a huge impact on the effectiveness of extraction procedures [40]. Furthermore, the efficiency of recovering specific bioactive compounds is greatly affected by the cellular structure of the by-product [41]. As reported by Soquetta [42], extraction methods can be broadly classified into nonconventional and conventional approaches. Conventional techniques, such as such soxhlet extraction, solvent extraction, maceration, and hydrodistillation commonly rely on organic solvents including athanol, methanol, and acetone, along with controlled temperature and agitation conditions [42]. To ensure maximum recovery while preserving the stability of bioactive compounds, key operational parameters such as temperature, extraction time, pH, particle size, solid-to-liquid ratio, and stirring speed must be carefully optimized. Although conventional extraction techniques are commonly employed, they suffer from several limitations, such as long extraction times, high solvent requirements, generation of

toxic waste, and the need for additional purification steps to remove solvent residues and impurities [43]. To address these limitations, modern or unconventional extraction methods have been developed as faster, cleaner, and more efficient alternatives. These include enzyme assisted extraction, pressurized liquid, pressured liquid extraction, supercritical fluid extraction, microwave-assisted extraction, ultrasound-assisted extraction, and pulsed electric field-assisted extraction. Compared with traditional approaches, these techniques generally provide higher extraction efficiency, reduce solvent consumption, short processing times, and lower energy requirements [44, 45].

Deep eutectic solvents (DESs) and their bio-based counterparts, known as natural deep eutectic solvents (NADESs), have emerged from the need of cost-effective and environmentally friendly extraction media. These novel solvents are particularly attractive for food waste valorization due to their low toxicity, biodegradability, and strong ability to dissolve a wide range of biomass components. DESs and NADESs have been successfully applied to extract valuable compounds from diverse sources, including lignocellulosic materials, bark, wood, algae, dairy and beverage wastes, and residues from vegetable oil processing [46, 47]. The flexibility of this approach is further demonstrated by the efficient recovery of phenolic compounds from pear, tomato, olive, and onion wastes using a simple, inexpensive, and eco-friendly NADES composed of lactic acid, glucose, and water. The use of such solvents enhance the sustainability of food waste extraction and enables the food industry to obtain high-quality

functional ingredients [46]. Given the significance potential of food and agricultural wastes as source of value-added compounds, many studies have focused on refining extraction techniques to maximize recovery while minimizing environmental impact. These techniques enhance extraction efficiency and selectively align with green chemistry principles, making them particularly suitable for valorization of food and agricultural by-products [48]. Selected case studies illustrating the recovery of valuable compounds from agro-food wastes, along with the extraction methods and key outcomes, are summarized in Table 2. Ultrasound assisted extraction creates during sonic cavitation, ultrasound vibrations rupture plant tissue, facilitating the quicker release of extractable components. Bioactive substances are extracted by ultrasound from food

waste and byproducts of fruits and vegetables. Microwave assisted extraction enhances molecular motion by increasing the solvent's ability to disrupt hydrogen bonds within the sample matrix, allowing the target compounds to dissolve more efficiently into the extraction fluid. Pressurized liquid extraction uses high temperatures (40–200 °C) and pressures (3.3–20.3 MPa), making molecules more soluble and desirable. Further Enzyme assisted extraction ensures that the cytoplasmic content moves through the extraction fluid, like water, by taking advantage of enzymes' ability to degrade the cell wall compartment. As this technique employs water as the extraction solvent rather than organic solvents, it is widely recognized as an environmentally benign and sustainable approach.

Table 2: Case Studies: Extraction of Valuable Compounds from Agricultural Food Wastes and By-products.

Food Waste / By-product	Extraction Method	Optimal Conditions	Extracted Compounds & Key Findings	Ref(s)
Pomace from kiwi juice	By microwave	Microwave power: 400 W, 350 psi, 50% ethanol:water, solid-to-solvent ratio 1:15, 75 °C, 15 min	High bioactive compounds: total phenolics, flavan-3-ols, ascorbic acid; strong antioxidant potential	[49]
Pistachio hard shells	Solvent extraction / Microwave-assisted extraction	Microwave-assisted: EtOH, 1000 W, 270 s	Total polyphenol: 4.8 ± 0.1 mg GAE/g; total flavonoid: 1.38 ± 0.01 mg CAT/g; ascorbic acid: 120.6 ± 0.5 mg/100 g	[50]
Hard shells of pistachio	Ultrasound-assisted extraction / Conventional organic solvents	Solvent: hexane:acetone:ethanol (2:1:1 v/v/v), 0.05% BHT, solid-liquid ratio 1:35 w/v, 15 °C, 90 W, 15–30 min	Gallic acid, monogalloylglucose isomer, pentagalloylglucose, kaempferol	[51]
Tomato processing waste	Ultrasound-assisted extraction / Maceration	Ultrasound: 60% amplitude, 60 °C, 5 min; Maceration: 50 °C, 8 h	Lycopene (76.87 mg/kg), β -carotene (6.12 mg/kg)	[52]
pulp of Hot pepper	Ultrasound-assisted extraction	60% amplitude, 60 °C, 5 min	Higher capsaicin and phenolic content; improved antioxidant activity	[52]
Beetroot waste	Pressurized liquid extraction	40 °C, 7.5–12.5 MPa, 90 min, flow rate 3 mL/min	Total phenolic content: 7 ± 1 mg GAE/g; high global extract yield (36% w/w)	[53]
Grape pomace	Ultrasound-assisted / Microwave-assisted extraction	Microwave-assisted: 2% citric acid, 1000 W, 10 min	Total phenolics: 6.68 ± 0.05 mg GAE/g; total monomeric anthocyanins: 1.32 ± 0.03 mg/g; strong antioxidant activity	[54]
Sesame bran	Enzyme-assisted / Ultrasound-assisted extraction	pH 9.8, 1.248 AU enzyme, 836 W, 43 °C, 98 min	Protein and antioxidant compounds; total phenolics: 3.82–6.03 mg GAE/g; antioxidant capacity (DPPH, ABTS)	[55]
Coffee husk	Supercritical CO ₂ extraction	373 K, 300 bar, solvent-to-material ratio 197 kg CO ₂ /kg	Caffeine: 59% yield, 77% purity	[56]
Pumpkin seeds	Ultrasound-assisted three-phase partitioning	(NH ₄) ₂ SO ₄ 30 g/100 mL, t-butanol:slurry 1:1, pH 5, duty cycle 60%, 118 W, 20 min	Oil (39.79%), protein (14.30%), polysaccharides (1.97%); fatty acid composition detailed	[57]

Bioactive chemicals with anti-inflammatory, anti-cancer, antibacterial, antioxidant, and cardio metabolic health effects can be found in abundance in agricultural and food wastes [59, 60]. Because of their strong antioxidant potential, polyphenols especially those found in skins, seeds, pulp, or pomace are among the most significant phytochemicals [61]. Although consumer demand for natural antioxidants is rising, their direct use in food is frequently restricted due to their salts, poor solubility, light, sensitivity to oxygen, heat, enzymes, and pH, which lowers bioavailability and bioactivity, and chemical degradation during processing and gastrointestinal transit [59, 60]. Although consumer demand for natural antioxidants is rising, their direct use in food is frequently restricted due to their sensitivity to oxygen, poor solubility, pH, light, heat, enzymes, and salts, which lowers bioavailability and bioactivity, and chemical degradation during processing and gastrointestinal transit [61, 62]. Although consumer demand for natural antioxidants is steadily increasing, their direct

incorporation into foods is often limited due to sensitivity to oxygen, pH variations, light, heat, enzymes, and salts, as well as poor solubility. These factors can reduce their bioavailability and bioactivity, and promote chemical degradation during food processing and gastrointestinal digestion [62]. In this context, biotechnological approaches such as fermentation provide sustainable and effective routes for the valorization of food wastes by enhancing both the concentration and bioavailability of bioactive compounds. Fermentation involves the anaerobic breakdown of organic substrates and can be carried out as submerged, liquid, and solid state processes. Among these, solid state and submerged fermentation are most commonly employed for bioactive recovery. [63, 64]. Fermentation not only improves the nutritional and functional properties of the resulting products but also requires lower energy input, reduced cost, and generated minimal waste. Various strategies adopted to enhance the stability and

bioavailability of bioactive compounds derived from food wastes are summarized in Table 3

Table 3: Methods for Improving the Bioavailability and Stability of Bioactive Compounds from Food Waste

Food Waste / Byproduct	Approach / Technique	Key Outcomes	Ref(s)
Fruit peels (citrus, apple)	Spray drying (nano/microencapsulation)	Retained polyphenols, improved antioxidant stability and solubility	[59]
Grape pomace	Nanoemulsion (protein–lipid matrices)	Enhanced polyphenol bioaccessibility and dispersibility	[60]
Tomato pomace	Coacervation / Microfluidics emulsions	Lycopene stability, increased bioavailability	[61, 62]
Mango peel	W/O/W emulsions	High encapsulation efficiency (98.65%), improved storage stability	[65]
Berry wastes (strawberry, blueberry)	Freeze-drying with cyclodextrin	Protected anthocyanins, improved solubility	[59]
Onion / garlic wastes	Alginate nanoparticles	Increased phenolic stability, controlled release	[61]
Vegetable pomace (carrot, beet)	Liposome nanoencapsulation	Enhanced β -carotene and phenolic bioavailability	[62]
Seed wastes (pumpkin, sesame)	Protein–polysaccharide coacervation	Increased antioxidant retention	[59, 60]
Agro-industrial wastes	Fermentation (solid-state, submerged, liquid)	Increased phenolics, flavonoids, antioxidant activity, and bioaccessibility	[43, 66]

Ongoing concerns regarding the safety and acceptability of synthetic food additives have encouraged the food industry to explore natural alternatives derived from low-cost sources of proteins, colorants, flavouring agents, antioxidants, dietary fibers and antimicrobials [62, 67]. By valorizing food and agro-industrial wastes as natural ingredients, industries can reduce waste management costs, create additional revenue streams, and develop products that are both nutritionally enhanced and commercially attractive. By reducing antinutritional elements, biotechnological methods can also provide byproducts that can be used to create balanced food compositions. The majority of small traders continue to dispose of waste incorrectly, even if some local communities find innovative ways to use residues. The Environmental Protection Agency (EPA) prioritizes using excess for human consumption, then animal feed, industrial applications, and composting or incineration in order to remedy this [43]. In addition to providing nutrients and bioactive chemicals, using food wastes as natural additives necessitates consideration of sensory qualities and consumer acceptability. For example, pineapple or white chocolate-

flavored jelly samples enhanced with chicken foot collagen were rated favorably by tasters [68]. However, despite their attractive labeling, cookies enhanced with blueberry pomace were not as popular as the reference vanilla cookies [69]. Additionally, there are financial, nutritional, and environmental advantages to valuing food waste. In order to support programs like the Zero Hunger Challenge and UN Sustainable Development Goals, industries are increasingly pursuing "zero-waste" techniques, turning leftover biomass into raw materials for new goods [43]. For instance, the GEA Pro-Enrich project uses energy-efficient and economical techniques to extract pigments, dietary fibers, antioxidants, and functional proteins from fruit and vegetable residues, such as tomato, citrus, olive, and rapeseed byproducts, for use in adhesives, pet food, cosmetics, and dietary supplements [70]. Representative case studies on the application of food waste-derived additives in different food products, along with their functional components and outcomes, are compiled in Table 4.

Table 4: Application of Food Waste-Derived Additives in Food Products

Food Waste / Byproduct	Food Product / Application	Functional Component / Purpose	Key Outcome / Consumer Acceptance	Ref(s)
Chicken feet	Jelly (pineapple, white chocolate)	Collagen	Good sensory acceptance; consumers willing to consume	[68]
Blueberry pomace	Cookies	Antioxidant fiber	Acceptable labeling; lower preference than reference cookie	[69]
Tomato residues, citrus peels, olive pomace, rapeseed meal	Dietary supplements, pet food, cosmetics, adhesives	Functional proteins, phenolics, dietary fibers, pigments	High-quality extracts for multiple industrial applications	[70]
Fruit and vegetable byproducts (general)	Various food products	Bioactive compounds, natural colorants, antioxidants	Supports zero-waste and functional food development	[43]

Agro By products as Animal Feed

Cereal husks, fruit and vegetable peels, pulp, and bagasse are examples of agro-industrial wastes that could be used as substrates to create animal diets with added nutrients. Conventional feed products, which give animals vital macronutrients and energy, include blended raw residues, green/dry fodder (hay, silage, pasture), and formulated compound feeds. Nevertheless, these residues frequently contain anti-nutritional factors (ANFs) that restrict the availability and digestion of nutrients, including hydrogen cyanide, caffeine, polyphenols, oxalates, phytates, tannins and saponins. In addition, food and processing wastes

typically possess high moisture content and readily degradable organic matter, which make them highly susceptible to rapid microbial spoilage and contamination [71]. Poor segregation practices can result in the presence of plastics, metals, chemical residues, and pathogenic microorganisms, thereby raising significant safety concerns for their use in animal feed. Furthermore, improper storage conditions may promote the formation of mycotoxins particularly aflatoxins which pose serious health risks to livestock [72]. To get around these restrictions, microbial valorization especially through Solid-State Fermentation (SSF) offers a safe and affordable solution. To convert solid

organic wastes into value-added products like protein-rich feed, enzymes, bio-pigments, biofertilizers, and biofuels, SSF uses GRAS microorganisms, such as filamentous fungi (like *Aspergillus niger* and *Rhizopus oryzae*), yeasts (like *Saccharomyces cerevisiae*), and bacteria (like *Bacillus* spp. and *Lactobacillus* spp.) [73, 74, 75]. By increasing digestibility, decreasing ANFs, and increasing protein content, SSF improves the nutritional quality of agro-industrial residues. The biotransformation approach helps address protein deficiencies in livestock diets by enabling the production of safe, low cost feed alternatives. Cereal residues from sorghum, oats, corns, millet, and barley are widely valorized, while cereal by-products such as wheat bran, rice bran, and middlings are commonly used as feed concentrates or dietary supplements, particularly in regions such as North America and Europe [76].

The selection of suitable substrates for solid-state fermentation (SSF) depends on factors such as their availability, lignocellulosic composition, carbohydrate content, and solid organic nature. Recent advances in microbial biotechnology and bioupgrading have further improve feed quality by promoting protein enrichment, reducing anti-nutritional factors and generating functional feed ingredients [73, 77]. Despite these benefits, improper disposal of agro-industrial wastes remain a significant challenge, underscoring the importance of adopting SSF and related bioprocessing strategies for sustainable animal nutrition. Utilizing entire organisms or their constituent parts, bioprocessing integrates expertise from chemical engineering, microbiology, biochemistry, and related disciplines to transform raw materials into valuable products with added value (Muenz, 2021). It produces a variety of goods, such as vitamins, animal feed, biofuels, biosurfactants, and antibiotics. In addition to production, bioprocessing provides a number of "green" benefits, such as (i) using biomass rather than fossil fuels, (ii) using renewable resources sustainably, (iii) replacing depleted fossil energy, and (iv) lowering greenhouse gas emissions from petroleum-based industries [78]. Food wastes typically contain high moisture levels and readily biodegradable organic matter, making them highly susceptible to rapid microbial spoilage if left untreated [79, 80]. Inadequate segregation during collection and handling may introduce contaminants such as plastics, metals, chemical residues, and pathogenic microorganisms, thereby necessitating thorough pretreatment before their use in animal feed [81]. Moreover, improper storage conditions significantly increase the risk of mycotoxin contamination particularly aflatoxins which pose serious threats to livestock health and

therefore require strict monitoring and control measures [82]. Notwithstanding these advantages, it is expensive and technically difficult to produce bioproducts from biomass. Agro-industrial wastes that are high in sugar and starch act as the main fermentation substrates in the near run. Lignocellulosic agricultural leftovers are a plentiful, affordable, and readily processed source of feedstock for long-term sustainability. Solid-State Fermentation (SSF) is a viable and cost-effective biotechnological approach for the valorization of agro-industrial residues, enabling the production of detoxified lignocellulosic materials, biofuels, animal feed and biopulp. By increasing protein content, improving essential nutrient availability, and reducing anti-nutritional factors (ANFs), SSF significantly enhances the nutritional quality of lignocellulosic wastes, making them suitable as safe and economical animal feed. Recent advances in bioupgrading and biotransformation technologies have further strengthened the potential of SSF as a sustainable strategy for improving animal nutrition.

By increasing protein content, improving essential nutrient availability, and reducing anti-nutritional factors (ANFs), solid-state fermentation (SSF) enhances the nutritional quality of agro-industrial residues and enables the production of safe and low-cost animal feed. Recent advances in bioupgrading and biotransformation technologies have further improved feed quality, strengthening the role of SSF as a promising strategy for sustainable animal nutrition.

The first and most critical step in SSF is the selection of appropriate microbial strains and substrates. Due to the nature and large particle size of many agro-industrial wastes, substrates are commonly chopped, ground, or crushed to increase surface area, facilitate microbial colonization, and improve nutrient availability [83]. To support microbial growth and product formation, many residues, including the peels of cassava, yam, and plantains, are nutritionally lacking and need to be supplemented with external nutrients, especially nitrogen sources (such as ammonium nitrate, ammonium sulfate, peptone, sodium nitrate, yeast extract, and urea) and trace elements [84, 85, 86]. Studies indicate that supplementation with only microelements or nitrogen sources is insufficient, emphasizing the need for a balanced nutrient composition [87].

Filamentous fungus (like *Aspergillus* and *Rhizopus*), yeasts (like *Saccharomyces*), and bacteria (like *Bacillus* and *Lactobacillus*) are among the microorganisms utilized in SSF. Because they are more resilient in solid media than in liquid ones, fungus spores are favored [88-91].

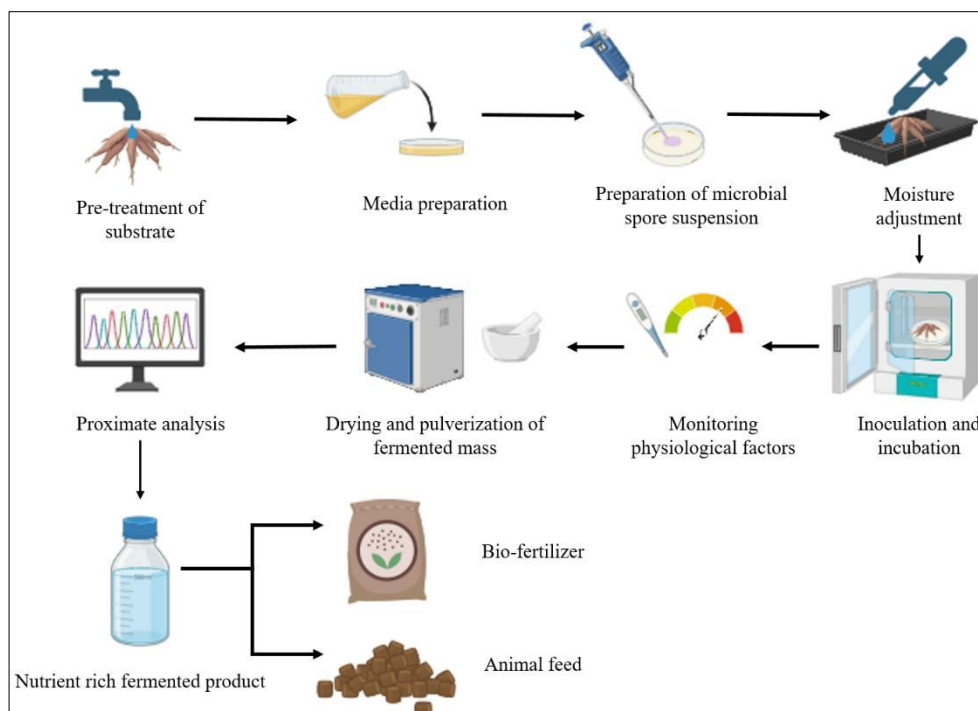


Fig 2: An outline of the procedures used to produce fermented animal feed

Conclusion

Agricultural and agro-industrial wastes represent a valuable yet underutilized resource with significant potential for the development of food, feed, and functional products. Advances in extraction technologies and bioprocessing approaches, particularly solid-state fermentation, have enabled the efficient recovery and enhancement of bioactive compounds from these residues. The integration of such strategies supports sustainable resource utilization, reduces environmental impact, and contributes to the circular bioeconomy. However, challenges related to scalability, economic feasibility, and consumer acceptance must be addressed to ensure wider industrial adoption. Future efforts should focus on developing cost-effective, integrated biorefinery systems and supportive policies to fully realize the potential of agricultural waste valorization.

Conflict of interest statement

The authors declare that they have no conflict of interest.

Acknowledgement

The authors would like to acknowledge the contributions and collaboration of their co-authors in the preparation of this review

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