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Agricultural plant jiaosu: valorization of organic wastes for sustainable agriculture

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Agricultural plant jiaosu (APJ) represents a novel and highly valuable ecological input with multiple applications. It is utilized as foliar fertilizer, drip irrigation fertilizer, bio-pesticide, and decomposing fungicide, facilitating the enrichment of local beneficial microorganisms and the efficient treatment of local organic waste. The technology offers the advantages of straightforward operation, minimal equipment requirements, and low cost. Its potential applications and research areas are extensive, with benefits including enhanced plant growth, improved crop quality, soil ecology enhancement, reduced environmental pollution, and prevention of crop pests and diseases. Despite its potential, there is a shortage of review papers on APJ in agricultural practices. This essay aims to provide an overview of the concept, categorization, preparation methods, and primary ingredients of APJ. It also discusses the impacts of APJ on agro-ecological systems and reviews current research, focusing on aspects such as raw material selection, microbial fermentation, the fermentation process, and detection technologies. However, further investigation and study are necessary due to the complex composition of APJ.

KEYWORDS
agricultural plant jiaosu, sustainable agriculture, fermentation, recycling, agroecological effect

1 Introduction

To ensure the continuous and efficient use of agricultural resources and ecological security, achieve sustainable agricultural development, and address the interplay between agricultural economic growth, resource utilization, and ecological environmental protection, agricultural practices must embrace sustainable pathways (Reganold and Wachter, 2016). Annual increases in chemical fertilizer consumption, driven by the goal of maximizing yields, have undeniably boosted productivity per unit area. However, the widespread use of chemical fertilizers has exacerbated rural ecological degradation and contributed to mounting solid waste (Pahalvi et al., 2021; Ding et al., 2021). The advancement of APJ technology is crucial for solving the contradiction between environmental pollution and sustainable agricultural development brought about by the increase of physical and chemical inputs (Barcelos et al., 2020).

According to Shimamoto Gakuya of the Institute of Microbiology in Nagoya, Japan, jiaosu was created and named after the presence of jiaosu bacteria. Jiaosu bacteria constitute a complex microbial agent consisting of yeasts, acetic acid bacteria, and lactobacilli, commonly found in the natural environment (Shimazono, 1996; Jikang et al., 2022). The Chinese Ministry of Industry and Information Technology announced

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two jiaosu standards on December 28, 2018: QB/T5323-2018, titled "Plant Jiaosu", and QB/T5324-2018 titled "Jiaosu Product Classification Guidelines" (Ministry of Industry and Information Technology of the People's Republic of China, 2018a,b). These standards indicate that APJ production primarily utilizes plants as raw materials, employing microbial fermentation to develop products with specific bioactive components for planting, farming, and soil enhancement, optionally incorporating auxiliary materials.

Despite the growing interest, there remains a paucity of published studies on the fermentation mechanism, process optimization, and ecological applications of APJ. Research in this area is still in its nascent stages.

This study aims to provide a comprehensive review of the current classification, processes, composition, agricultural applications, and challenges associated with APJ. Additionally, the study analyzes recent research progress on raw material selection, microbial fermentation, fermentation processes, and mechanisms. The overarching goal is to clarify the potential of APJ in fostering robust soil-microbe-plant agro-ecosystems and advancing sustainable agricultural practices.

The purpose of this review is also to investigate the potential applications of organic waste for the synthesis of APJ, as well as to evaluate the process's viability and constraints in light of existing technological advancements and potential benefits for the advancement of sustainable agriculture. The paper will specifically address the following three main issues: first, how to use organic waste for APJ preparation; second, how feasible and limited is it to use APJ to treat organic waste given current technological conditions; and third, how using APJ to treat organic waste promotes sustainable agricultural development and the particular environmental benefits that come with it.

The remainder of this paper is organized as follows: Section 2 outlines the methodology in accordance with PRISMA guidelines; Section 3 explores the classification of jiaosu, beginning with an overview of "jiaosu" and then delving into the APJ classification; Section 4 introduces the production process of APJ; Section 5 examines the main components of APJ; Section 6, which is the core focus, reviews the latest research progress on APJ from four key aspects; Section 7 discusses the agricultural impacts of APJ; Section 8 summarizes the current problems and challenges; Section 9 provides insights into future perspectives; Section 10 offers specific recommendations; and finally, Section 11 concludes with a summary of the main findings and conclusions of the study.

2 Methods

We conducted a thorough analysis of the pertinent scientific literature using the Procedure for Systematic Reviews and Meta-Analyses (PRISMA) (Page et al., 2021) (Figure 1). To systematically review APJ and its applications in sustainable agriculture, we conducted a comprehensive search of the literature using multiple databases to ensure a thorough identification of relevant studies. The databases searched include PubMed, Web of Science, and Google Scholar (Falagas et al., 2008). The search period was from 1995 to 2024, focusing particularly on the years 2020–2023, where significant advancements and detailed research were reported, as shown in Figure 2.

The search strategy employed a combination of keywords and Medical Subject Headings (MeSH) terms where applicable. The following keywords and their combinations were used: "agricultural plant jiaosu," "sustainable agriculture," "fermentation," "recycling," "agroecological effect," "biopesticides," and "waste enzymes."

2.1 Inclusion criteria

The inclusion criteria for this study are as follows: research that focuses on the classification, production processes, composition, and agricultural applications of APJ; studies examining fermentation mechanisms, process optimization, and the ecological impacts of APJ; investigations into the use of organic waste for enzyme preparation and its implications for sustainable agriculture; and articles providing insights into the agricultural effects of APJ and the challenges associated with its implementation.

2.2 Exclusion criteria

The exclusion criteria for this study include studies that are not directly related to APJ or sustainable agricultural practices, review articles that do not provide original data or insights, and publications not available in English.

2.3 Search strategy and filters

The search was conducted using advanced search features within each database (Bramer et al., 2018). Filters were applied to limit the results to peer-reviewed articles, reviews, and conference papers. Time filters were set to include only publications from 1995 to 2024. Additionally, language filters were applied to include only English-language publications to enhance search efficiency.

2.4 Study selection process

1. Identification: Using the defined search strategy, initial retrieval of records was performed. Through keyword combinations, we ensured that as many relevant documents as possible were captured.

2. Screening: Titles and abstracts were screened according to the inclusion criteria to identify potentially relevant studies. Two researchers independently conducted the screening, resolving any discrepancies through discussion.

3. Eligibility: The full texts of potentially relevant studies were reviewed to confirm their eligibility based on the inclusion and exclusion criteria. Each researcher independently assessed the full texts of each article to ensure that all eligible studies were included.

4. Inclusion: The final selection of studies for inclusion in the review was made. For studies with conflicting eligibility, consensus was reached through group discussions.

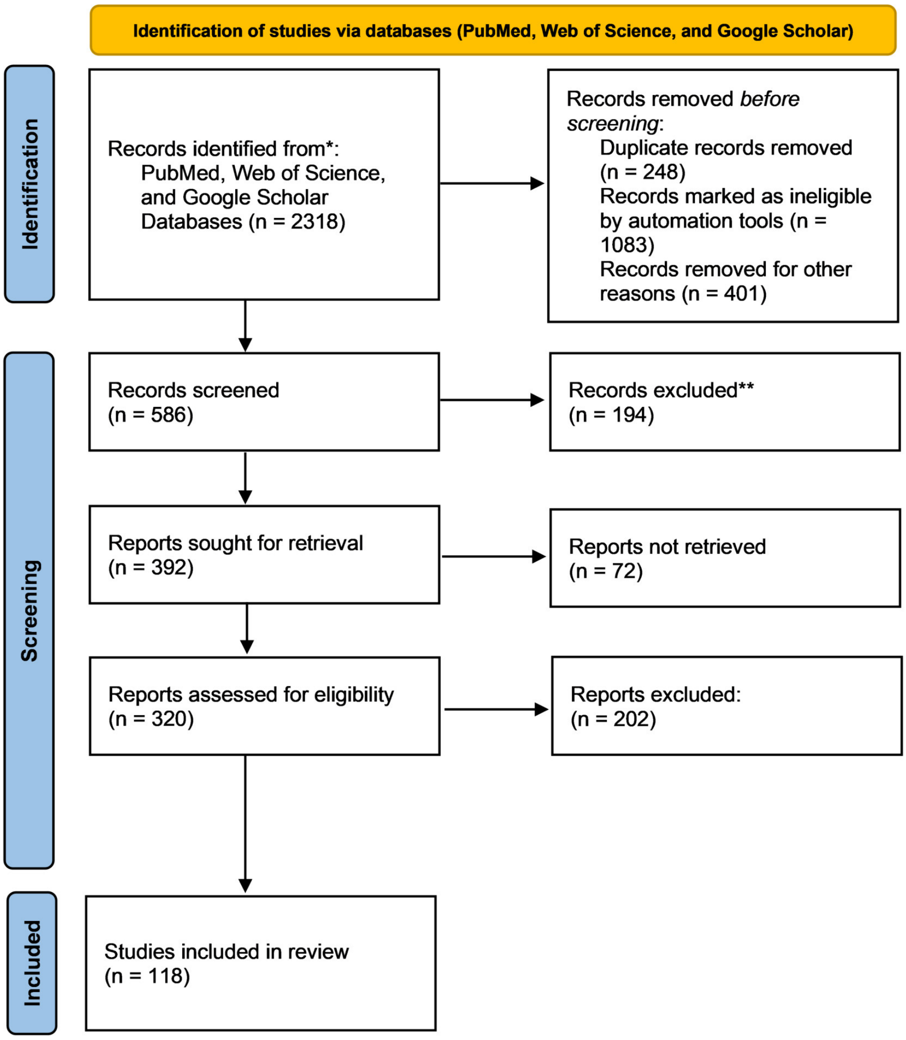

FIGURE 1
PRISMA flow diagram for systematic review.

2.5 Data collection and analysis framework

Key information such as study design, sample size, methods, results, and conclusions were extracted from the included studies. Studies were categorized based on their focus areas, including APJ classification, production processes, composition, and agricultural applications. A comprehensive analysis was performed to synthesize the findings across studies and identify trends and gaps in the research. Both qualitative and quantitative methods were used for data analysis, with results presented in charts and tables (Mitsui et al., 2004). The categorization of articles used in this study is shown in Figure 3.

2.6 Reference checking

To ensure comprehensiveness, the reference lists of included articles were also checked for additional relevant studies. This helped identify potentially overlooked important literature and expanded the scope of the review.

3 Classification

The applicable rules and norms distinguish three categories of APJ: planting, farming, and soil improvement. A detailed explanation of the APJ classification system follows Figure 4. In addition, Jiaosu products span various industries and forms, categorized from multiple perspectives. In terms of application, they fall into agricultural categories (e.g., growth-promoting, pest control, disease resistance, and soil improvement jiaosu), edible categories (e.g., apple, brown rice, shiitake mushroom, and rose jiaosu), environmental protection categories (e.g., deodorizing, air purification, and water purification jiaosu), daily use (e.g., cleaning, skin care, oral care, and washing jiaosu), feeding (e.g., pet and livestock feed jiaosu), and other miscellaneous jiaosu products. Based on raw materials used in fermentation, jiaosu can be classified into plant-based (e.g., pumpkin, fruits), fungal (e.g., tremella, Cordyceps sinensis), animal-derived (e.g., donkey-hide gelatin, fish protein), and mixed (from two or more plant, fungal, or animal sources). Furthermore, jiaosu products are categorized by their

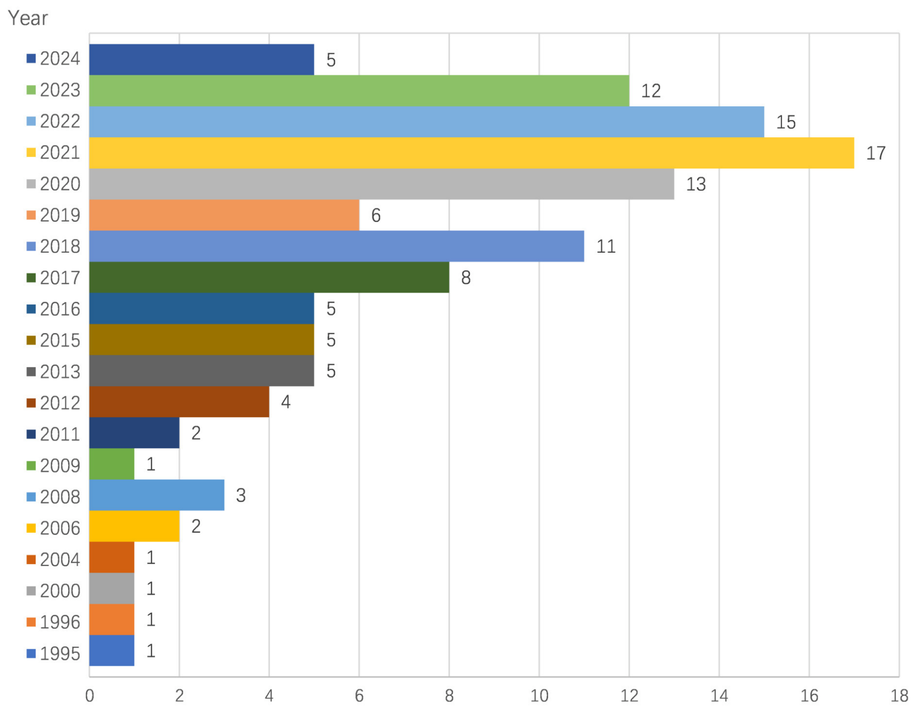

FIGURE 2
The number of searched articles on year.

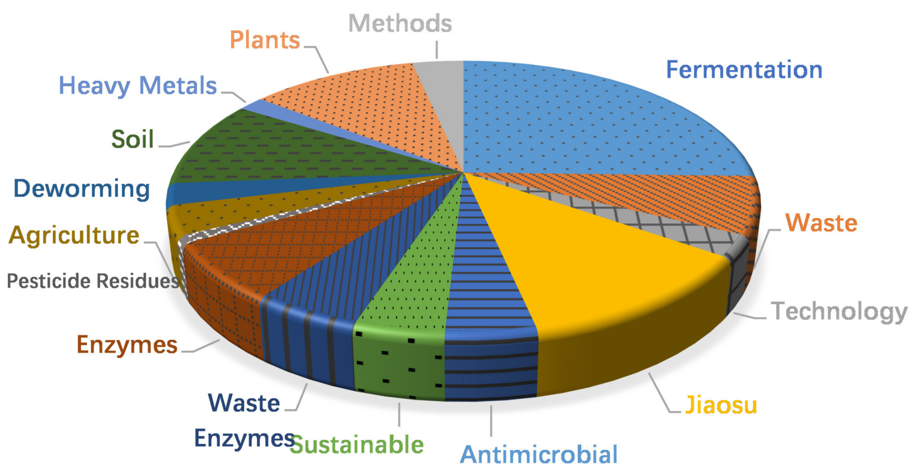

FIGURE 3
The categorization of searched articles.

physical form into liquid jiaosu (e.g., jiaosu liquid), semi-solid jiaosu (e.g., jiaosu paste), and solid jiaosu (e.g., jiaosu powder). The fermentation processes are categorized into group fermentation (e.g., natural fruit and vegetable fermentation), composite fermentation (e.g., combined fruit and vegetable fermentation), and pure fermentation (e.g., using specific microbes like lactobacillus plantarum or Natto bacteria) (Ministry of Industry and Information Technology of the People's Republic of China, 2018a,b; Dai et al., 2020).

3.1 For the planting industry

Plant jiaosu is primarily used to enhance crop growth by improving resilience (such as resistance to drought, pests, and diseases), promoting root formation, enhancing photosynthetic efficiency, and optimizing nutrient uptake through biotechnological methods (Zhang et al., 2022). Its rich blend of beneficial microbes, potent enzymes, and natural organic matter significantly boosts crop resilience, bolstering both drought

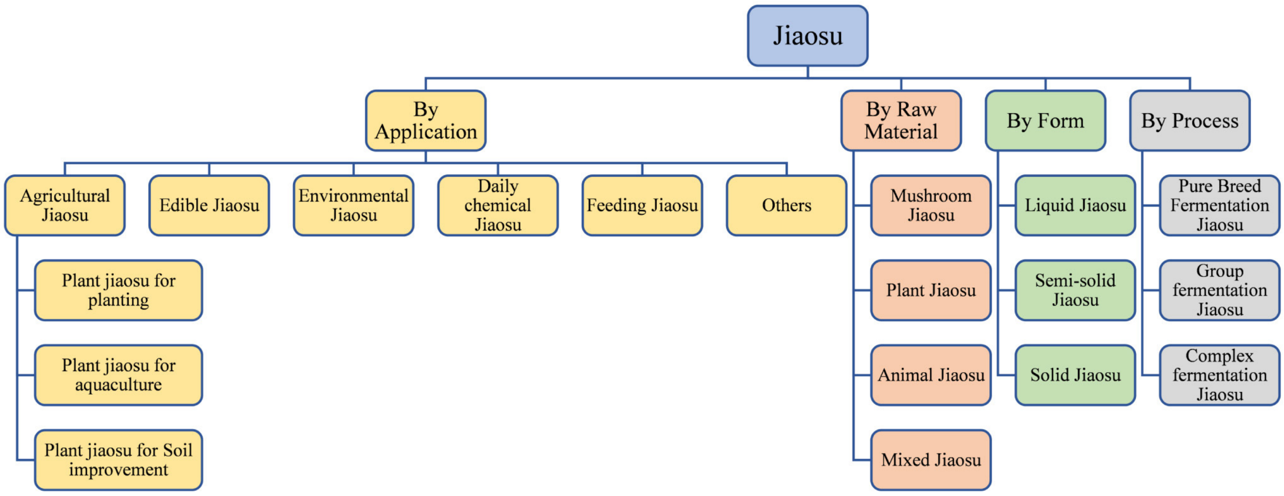

FIGURE 4
Classification of jiaosu.

resistance and natural defenses against pests and diseases, thereby enhancing overall agricultural sustainability. Moreover, it stimulates deep root growth and efficient nutrient absorption, leading to improved photosynthesis and nutrient-rich crop growth, thereby achieving higher yields and enhanced quality. Plant jiaosu plays a pivotal role in promoting ecological and sustainable agricultural practices by regulating soil microecological balance, and creating a more conducive environment for crop cultivation (Prasad and Raghuwanshi, 2022; Flores-Gallegos and Nava-Reyna, 2019).

3.2 For the farming industry

Plant jiaosu used in aquaculture aims to boost animal immunity, improve intestinal health, increase feed efficiency, and accelerate growth and development (Van Hai, 2015; Anadón et al., 2019; Liang et al., 2022; Khan et al., 2018). This biotechnological solution optimizes the aquaculture environment and promotes animal wellbeing by effectively enhancing the digestive tract environment with a balanced combination of microorganisms and enzyme systems. It maximizes nutrient absorption and utilization, minimizes feed wastage, and maintains a balanced intestinal microbial ecosystem, bolstering the immune defenses of livestock, poultry, and aquatic animals. Consequently, this approach significantly reduces the incidence of animal diseases and decreases reliance on antibiotics, promoting environmentally sustainable aquaculture practices while ensuring food and environmental safety (Chen J. et al., 2020).

3.3 For soil improvement

The primary purposes of jiaosu, a plant for improving soil, are fertility and soil structure. It is dedicated to repairing and maximizing the soil environment and deftly blends rich organic materials and active microbes through the natural fermentation process. Numerous beneficial microorganisms, including cellulolytic and phosphate-solubilizing bacteria, are present in jiaosu (Bayer et al., 2006). These microorganisms not only have the ability to break down complex soil organic matter and release immobilized nutrients (Datta, 2024), including phosphorus, potassium, and other micronutrients, to lessen the need for chemical fertilizers, but they also excel at enhancing the physical proper-ties of the soil (Ch et al., 2017), such as improving aerobics and water-holding capacity, to improve the growing environment for crops. The acidic compounds in jiaosu can raise the pH to the ideal range for crop growth, encourage the development of granular structure, and improve the soil's ability to retain water and fertilizer (Wu et al., 2022). More significantly, by boosting microbial diversity, the soil amendment plant jiaosu creates a stable and effective microbial ecosystem (Prasad and Raghuwanshi, 2022; Ablimit et al., 2022). This solves the issue of soil degradation at its source and provides a strong ecological basis for the growth of crop roots. It also paves the way for the implementation of a sustainable, effective, and ecologically friendly mode of modern agricultural production.

Table 1 presents the detailed labeling of the physicochemical indices for planting, farming, and soil improvement plant jiaosu. In addition to giving producers a foundation for quality control, the explanation of these physicochemical indexes aids users in the rational and scientific selection and application of plant jiaosu products to maximize agricultural productivity and environmental protection.

4 The production process of APJ

A brown and sour fermented product known as jiaosu is produced from agricultural plants. It involves fermenting a mixture of sugar, organic waste, and water in a closed container for over 3 months, maintaining a mass ratio of 1 part sugar to 3 parts organic waste to 10 parts water (Benny et al., 2023). Creating a

TABLE 1 Classification and indicators of agricultural plant jiaosu.

Plant jiaosu species	Indicators	Morphology	
		Liquid	Solid
Plant jiaosu for planting	pH	≤8.0	≤8.0
	Moisture	—	≤30%
	Organic matter	≥5 g/L	≥45 g/kg
	Organic acids (lactic acid)	≥1 g/L	≥5%
	Effective viable bacteria count	≥1 × 10^7 CFU/mL	≥1 × 10^7 CFU/g
	Trace elements	≥2 g/L	≥1 g/kg
	Amino acids	≥10 g/L	≥15 g/kg
	Oligosaccharides	≥5 g/L	≥5 g/kg
	Protease activity	≥100 U/L	≥500 U/kg
	β-glucanase activity	≥200 U/L	≥1,000 U/kg
	Polyphenol	≥0.1 g/L	≥0.05%
	Crude polysaccharide	≥20 g/L	≥10%
Plant jiaosu for aquaculture	pH	≤7.5	—
	Moisture	—	≤30%
	Ethanol content	≤0.8 g/L	—
	Effective viable bacteria count	≥1 × 10^7 CFU/mL	≥1 × 10^7 CFU/g
	Amino acids	≥15 g/L	≥15 g/kg
	Free amino acids	≥10 g/L	≥5 g/kg
	Total acid	≥5 g/L	≥15 g/kg
	Organic acids (lactic acid)	≥1 g/L	≥5 g/kg
	Crude polysaccharide	≥10 g/L	≥15 g/kg
	Oligosaccharides	≥5 g/L	≥5 g/kg
	Protease activity	≥100 U/L	≥500 U/kg
	α-amylase activity	≥200 U/L	≥1,000 U/kg
	Lipase activity	≥50 U/L	≥200 U/kg
Plant jiaosu for soil improvement	pH	≤7.5	≤7.5
	Moisture	—	≤30%
	Organic acids (lactic acid)	≥1 g/L	≥5 g/kg
	Effective viable bacteria count	≥1 × 10^7 CFU/mL	≥1 × 10^7 CFU/g
	Organic matter	≥5 g/L	≥45 g/kg
	Trace elements	≥2 g/L	≥1 g/kg
	Amino acids	≥10 g/L	≥10 g/kg
	Crude polysaccharide	≥20 g/L	≥15 g/kg

resource cycle by producing APJ for cultivation (Figure 5). Fresh, organic leftovers such as melon peels, vegetable leaves, and roots are collected, ensuring any moldy or rotten parts are removed before chop-ping them into small fragments. Brown Sugar, which contains more minerals and trace elements than sugar, is preferred for microbial fermentation (Zhang L. et al., 2013).

Next, enough clean tap water is added to cover all the chopped vegetable debris, leaving 70% to 80% of the container space free to allow for fermentation gas. The mixture is gently stirred and then left to ferment in an environment between 25°C and 35°C. Periodically, typically once a week, the container lid is opened to release gas and gently agitate the mixture to promote consistent fermentation.

After fermentation, the jiaosu appears as a brown liquid with a subtle fruity aro-ma and no pronounced odor. APJ is obtained by centrifuging the fermented mixture for 20 min at 6,000 rpm and then filtering out the solid residue. It should be transferred to an airtight container and stored in a cool location.

When applying, spread it evenly over the soil's surface and around plant leaves at a dilution ratio of 1:1,000. This application method strengthens soil structure, promotes plant growth, enhances disease resistance, and aids in pest management.

5 The main composition of APJ

APJ contains a diverse array of bioactive substances that enhance soil structure, promote microorganism activity, boost plant resistance, and provide essential nutrients (Yuliandewi et al., 2018). These mechanisms collectively improve crop yield, enhance crop quality, and contribute to the sustainability of agricultural production.

The main composition includes:

1. Enzymes: Enzymes presented in APJ originate from plants and include protease, cellulase, pectinase, and others. These enzymes are produced by microbes during fermentation, facilitating the rapid transformation and breakdown of organic matter (Tang and Tong, 2011a). This process enhances soil fertility and promotes efficient nutrient ab-sorption by plants (Zhang et al., 2015).

2. Organic acids: Organic acids found in APJ include acetic, citric, and malic acids. These acids contribute to improving soil structure, pH balance, and microbial activity. Additionally, they aid in chelating metal ions and enhancing the effective-ness of trace minerals (Punniamoorthy et al., 2024; Mudaliyar et al., 2012).

3. Amino Acids: As an important nutrient for plant growth, amino acids not only directly supply sources of nitrogen but also increase the efficiency with which other nutrients are absorbed by plants, encourage the growth and development of plants, and strengthen their tolerance to stress (Tong and Liu, 2020).

4. Polysaccharides: Polysaccharides found in APJ comprise oligosaccharides generated through microbial fermentation as well as polysaccharides like plant gum, pectin, hemicellulose, etc. These polysaccharides can strengthen the structure of soil aggregates, increase fertilizer and water retention, and give soil microbes energy, thereby promoting biological activity in the soil (Mohammed et al., 2021).

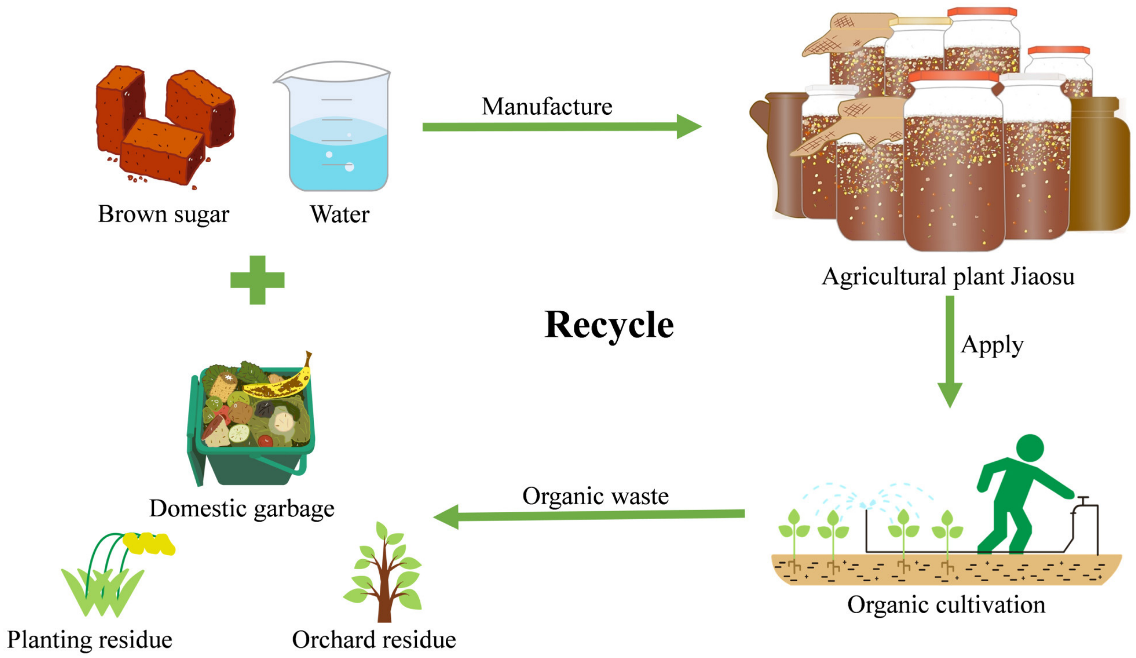

FIGURE 5
Recycling flowchart of agricultural plant jiaosu.

5. Phenols, flavonoids, polyphenols, and other secondary metabolites: these sub-stances are produced by microbiological metabolism from plant source materials and have potent antiviral, antibacterial, and antioxidant qualities that help strengthen plant defenses against disease and insect pests (Rana et al., 2022; Bouarab-Chibane et al., 2019).

6. Probiotics and biological enzymes: The good microorganisms (like Bacillus, lactic acid bacteria, and others) released during fermentation, along with the enzymes they secrete, help to maintain soil health, improve the structure of the soil microbial community, and encourage nutrient cycling (Zhang et al., 2023).

7. Vitamins, minerals, and trace elements: Vitamins, minerals, and trace elements in APJ are derived from the metabolism of plant raw materials and microbes during fermentation. These nutrients provide plants with comprehensive and balanced nutritional support, contributing to enhanced crop quality (Samtiya et al., 2021).

8. Antioxidant components: Antioxidant components in APJ, such as catalase, γ-aminobutyric acid (GABA), and superoxide dismutase (SOD), possess antioxidative and free radical scavenging properties. These compounds reduce plant stress responses and enhance plant resilience to environmental stress (Zhang et al., 2017; Liew et al., 2018).

6 The research progress of APJ

The fermentation broth, derived from microorganisms metabolizing organic plant waste, contains nutrients, biologically active compounds, and beneficial microbial flora, forming the core component of APJ—an ecological product with diverse applications (Arun and Sivashanmugam, 2015b). Various factors influence its characteristics and composition, including the composition and ratio of organic plant waste, fermentation temperature and duration, oxygen levels, agitation, and microbial inoculation (Singh et al., 2021). The composition of the fermentation substrate directly affects both the fermentation process and the final composition of the APJ (Behl et al., 2023). Key properties of organic plant waste, such as moisture content and particle size, significantly impact fermentation dynamics. Temperature, oxygen levels, and other factors also influence microbial diversity, indirectly affecting the fermentation process (Hossain et al., 2016).

6.1 Raw materials

The selection and proportion of raw materials used in jiaosu fermentation are critical factors that determine the quality and functional characteristics of the final product. Plant jiaosu typically utilizes fruits, vegetables, grains, and various medicinal foods as primary raw ingredients (Han et al., 2018).

6.1.1 Mixed substrates

Gao et al. (2023) utilized various fermentation substrates, including fruit wastes and herbal wastes, to produce the APJ. They observed that jiaosu fermented from composite substrates exhibited significantly higher bacterial diversity compared to those from single substrates. Furthermore, the concentrations of organic acids and secondary metabolites, as well as the composition of key microorganisms, varied depending on the richness of the substrate.

However, not all mixed-source jiaosu are necessarily superior to single-source jiaosu; superiority largely depends on the type of feedstock used. Jiang et al. (2021) produced five naturally fermented jiaosu variants, including single-source and mixed-source jiaosu from watermelon, cantaloupe, and orange. They analyzed their compositions and antioxidant capacities and found significant variations among the jiaosu types. Orange jiaosu exhibited the highest concentrations of total protein (9.46 ± 0.41 mg/ml), total phenol (0.32 ± 0.01 μ g/ml), and alcohol (56.51 ± 0.03 μ g/ml). Watermelon jiaosu showed the highest antioxidant capacity, while the watermelon-cantaloupe blend jiaosu demonstrated unique characteristics. This study highlights that the choice of raw material critically influences the composition and antioxidant capacity of jiaosu.

6.1.2 Functional substrates

Rasit et al. (2019) demonstrated that jiaosu can be prepared from orange and tomato peels with effective disinfectant properties for the treatment of aquaculture sludge and due to the high content of organic acids, the use of orange jiaosu showed higher removal rates compared to tomato jiaosu. The jiaosu prepared from citrus peels can also be used as a plant growth promoter for the treatment of metal-based wastewater and large quantities of organic wastes, heavy metals, and other wastes that have increased due to industrialization (Cherekar, 2020; Hemalatha and Visantini, 2020).

Moreover, Li et al. (2022) investigated the use of Chinese herbs (*Gynostemma pentaphyllum* and *Houttuynia cordata*) as raw materials for making jiaosu products, *H. cordata* contains a variety of polyphenols that are believed to be responsible for antioxidant activity (Huang et al., 2021; Mishra et al., 2021; Ma et al., 2015). More importantly, *H. cordata* has a preventive and therapeutic effect against novel coronaviruses such as SARS-CoV-2 (Bahadur Gurung et al., 2021). *G. pentaphyllum* is also a traditional Chinese herb that contains a variety of chemical components, resulting in its antioxidant and anti-inflammatory properties (Ji et al., 2018; Mastinu et al., 2021). Meanwhile, *G. pentaphyllum* has been shown to have a favorable preventive and prophylactic effect against many viral infections (Okoye et al., 2012). The study results demonstrated that the herbal plant jiaosu is rich in total protein, total sugars, vitamin E, and polyphenols, exhibiting high levels of total protein content and strong antioxidant capacity.

Some jiaosu raw materials include aromatic plants that contain various active substances such as alkaloids, phenols, and polysaccharides (Cai et al., 2020). Jiaosu nutrient solutions prepared from these plants exhibit enhanced antibacterial and anthelmintic effects (Stjernberg, 2000; Eckard et al., 2017). Although fermented raw materials are easily obtainable, careful selection of raw materials remains crucial for jiaosu production. This is due to variations in active ingredients and microbial populations among different materials, which can significantly influence the flavor, texture, nutritional content, and functional properties of the final product.

6.2 Microorganisms

The fermentation of jiaosu products can be classified into natural fermentation, inoculated fermentation, and combined natural and inoculated fermentation based on the fermentation method (Dai et al., 2020). APJ is predominantly fermented through natural fermentation utilizing Indigenous microorganisms such as yeasts, lactic acid bacteria, and Aspergillus oryzae present on the surface of raw materials (Voidarou et al., 2021). However, this method is associated with drawbacks including lengthy preparation times (exceeding 3 months) and susceptibility to contamination by extraneous bacteria, leading to variability in the quality of jiaosu products (Cruz-Casas et al., 2021). Research has shown that fortifying jiaosu fermentation with selected bacterial strains (Liu et al., 2019) can mitigate contamination risks, shorten fermentation times, and enhance product quality to some extent. Bio-enhanced fermentation involves selecting appropriate starter cultures based on the characteristics and intended use of raw materials, artificially inoculating them into the fermentation system before fermentation, and utilizing microbial flora to ferment fruit-based raw materials (Zhang et al., 2024). Depending on the strain used, fermentation can be categorized into pure strain fermentation with a single strain or mixed fermentation with a combination of multiple strains (Dudek et al., 2022).

6.2.1 Inoculated fermentation

Jikang et al. (2022) compared Pleurotus eryngii jiaosu inoculated with *Leuconostoc mesenteroides* and *Lactiplantibacillus planetarium* to naturally fermented jiaosu, assessing physicochemical characteristics (pH, acidity, reducing sugars), microbial counts, superoxide dismutase activity, and metabolomics via GC-MS. They found that inoculated strains significantly outperformed naturally fermented jiaosu, showing notable differences in metabolites such as sugars, acids, and alcohol. Sun et al. (2023) investigated naturally fermented and Lactobacillus plantarum-inoculated Akebia trifoliata fruits to enhance antioxidant activity in APJ. Their results indicated that inoculated fermentation resulted in higher acidity, lower pH, and more complete fermentation. Furthermore, flavonoid antioxidants produced through inoculated fermentation were 41.67% higher than those from natural fermentation, and phenol content during mid to late fermentation stages was also elevated compared to natural fermentation. These findings underscored the superior tolerance and stronger antioxidant capacity of inoculated fermentation. Overall, the studies demonstrated that inoculated fermentation of jiaosu surpasses natural fermentation in terms of shorter fermentation periods, higher efficiency, and superior product quality.

6.2.2 Mixed bacteria fermentation

In food jiaosu production, using a single bacterium often leads to poor flavor and functionality. For instance, lactobacilli fermentation alone can result in excessive acidity and a bitter taste, while yeast fermentation alone can yield a denser texture (Pang et al., 2021). Conversely, mixed-strain fermentation enables synergistic complementarity among strains, enhancing the overall quality and functionality of jiaosu products (Fan et al., 2023). Introducing new strains can further augment these benefits. Zou et al. (2022) demonstrated that chestnut rose jiaosu fermented with a mix of *Lactobacillus deutschenbachia Bulgarian subspecies* and *Lactobacillus casei* exhibited superior quality compared to

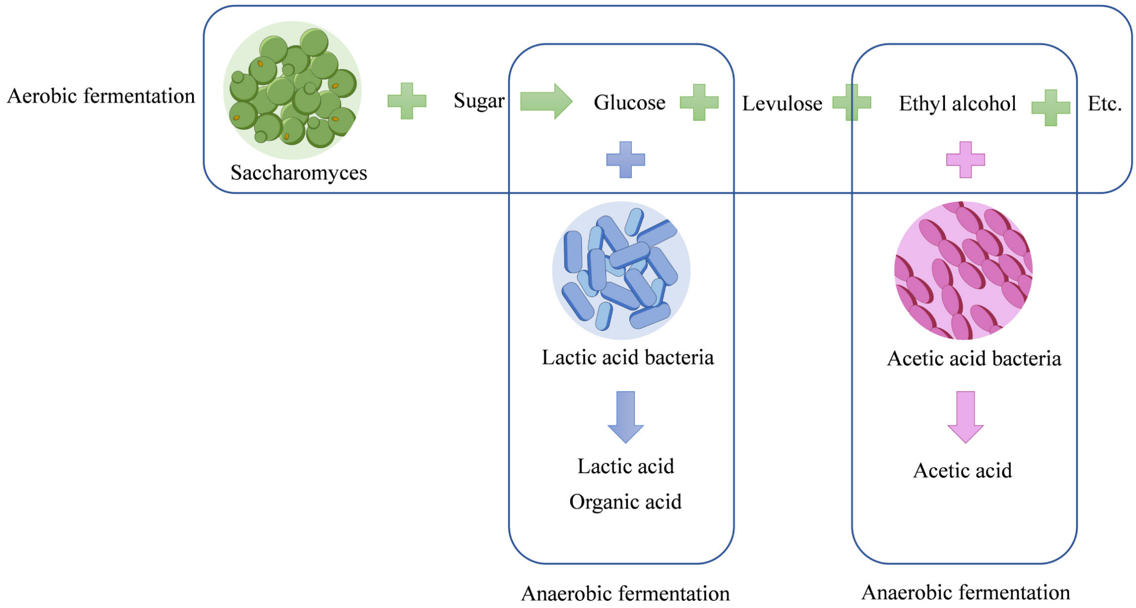

FIGURE 6
Fermentation mechanism diagram of agricultural plant jiaosu.

combinations involving other strains or single-strain fermentation. This superiority stems from collaborative interactions among different strains, leveraging their physiological advantages through physical and biochemical activities to optimize metabolic pathways.

The diverse range of plant raw materials and microorganisms involved in jiaosu preparation contributes to a complex fermentation mechanism and a challenging process to control (Fang et al., 2021). In current APJ mixed fermentations, lactic acid bacteria, yeast, and acetic acid bacteria are the predominant biofortified strains (Du et al., 2021). The fermentation of jiaosu can be broadly categorized into aerobic and anaerobic phases (Huanhuan et al., 2017). During the aerobic phase, anaerobic yeasts ferment vigorously, proliferating in a high-sugar environment (Maicas, 2020), thereby dominating the fermentation system. Yeasts break down complex sugars into glucose, fructose, ethanol, and other compounds (Broach, 2012). As oxygen levels decrease, acetic acid bacteria convert ethanol produced by yeasts into acetic acid, while lactic acid bacteria ferment glucose or lactose into organic acids such as lactic acid under anaerobic conditions (Stewart, 2017; Sievers et al., 1995). This process lowers the pH, inhibiting the growth of competing microorganisms. Concurrently, yeast populations decline, allowing lactobacilli and acetic acid bacteria to become dominant (Basinskiene et al., 2016) (Figure 6).

6.3 Fermentation technology

Whether it is natural fermentation or inoculation fermentation, the fermentation process of jiaosu is very complex. The quality of jiaosu products is not only related to the quality of raw materials, but also affected by the amount of inoculation, the amount of auxiliary materials added, the fermentation temperature, the fermentation time, and the ratio of liquid to liquid, etc.

Xu Y. Q. et al. (2023) developed ginseng jiaosu, the main active ingredient of ginseng is saponin, and rare saponins have specific antitumor effects. The fermentation process of ginseng jiaosu was optimized, and the best optimization method was the ratio of ginseng extract/concentrated apple juice/water as 1:1:10, the fermentation time as 16 d, the initial pH as 6.0, the fermentation temperature as 37°C, the sterilizing The amount was 1.0%, and after fermentation, the scavenging rate of hydroxyl radicals, DPPH radicals and superoxide anion radicals was increased by more than 9%, and new organic acids were produced.

Wang et al. (2019) explored the effect of fruit and vegetable fermented jiaosu on the intestinal flora composition of mice, in which fruit and vegetable jiaosu contained 66 ingredients (fresh fruits, vegetables, mushrooms, algae, and wild plants, among others), which were fermented for at least 300 days at a constant temperature of 37.5°C. The results of this study were summarized as follows. After mice were fed different concentrations of fruit and vegetable jiaosu for 15 days, it was found that the increase in beneficial flora in mice was positively correlated with jiaosu intake, and also altered the microbiota diversity of the mice's intestinal tract.

Zou et al. (2022) used chestnut rose as raw material, fermented with a mixed strain of *Lactobacillus deutschenbachia Bulgarian subspecies* and *Lactobacillus casei*, with a volume of chestnut rose juice in a mass ratio of 10:1.5 with sugar, and fermented at a temperature of 32°C for The fermentation was carried out at 32°C for 15 days, producing chestnut rose jiaosu with high SOD enzyme activity and optimal aroma, nitrite content of 94 mg/kg, and vitamin C content of 1,208 mg/100 mL.

As the jiaosu industry rapidly expands, increasing attention is being devoted to optimizing fermentation formulations and process conditions for jiaosu made from various raw materials. However, the majority of these studies focus on edible jiaosu, with fewer investigations into optimizing fermentation conditions for agricultural and vegetable-based jiaosu.

6.4 Technology

The structure and composition of the bacterial community in jiaosu were previously analyzed using the PCR-DGGE technique to investigate microbial metabolism and evolution during fermentation (Piterina and Pembroke, 2013). However, DGGE is limited to analyzing a select number of dominant microbial taxa, leading to potential overestimation of species abundance and underestimation of overall microbial community size and diversity (Duarte et al., 2012). Currently, the use of high-throughput sequencing technology can more comprehensively and accurately reflect the structure of microbial communities, and at the same time can more objectively reflect the low abundance of important functional microorganisms (Chen Y. et al., 2020). Therefore, it can be used to elucidate the changes in microbial community size and diversity and the alternation of dominant strains at different stages of jiaosu fermentation.

Zhang et al. (2023) applied high-throughput sequencing technology to analyze the physicochemical parameters of mulberry jiaosu and found that bioactive substances such as lactic acid, arginine, vanillic acid, and rutin increased significantly after 30 days of fermentation, which endowed the jiaosu with rich nutritional value, and that the diversity of fungi showed a trend of change in contrast to that of bacteria, and that Saccharomyces and Lactobacillus were important microorganisms in the fermentation process.

Fang et al. (2020) determined free radicals and reducing power during the fermentation of Yangmei jiaosu and analyzed organic acids using high-performance liquid chromatography. The study demonstrated that plant-derived jiaosu exhibits potent free radical scavenging ability, with organic acids playing a crucial role. In the fermentation process of Yangmei jiaosu, citric acid, and acetic acid are the primary organic acids, with total organic acid content significantly increasing and peaking at specific stages.

Hu et al. (2020) used high throughput sequencing to analyze three different blueberry jiaosu microbial community composition and diversity at the genus level, *Lactobacillus* spp., *Gluconobacter* spp., and *Acetobacter* spp. were the dominant bacteria, and *Dekkera* and *Issatchenkia* were the dominant fungi.

Ma et al. (2018) used single-molecule real-time sequencing (SMRT) to determine the bacterial microbiota of three jiaosu products purchased from Taiwan and Japan and found that despite the different sources of the three samples, they were highly similar in overall microbiota structure at the phylum level and no pathogen sequences were found throughout the data.

Untargeted metabolomics was employed by Jiang et al. (2024) to investigate metabolite variations between jiaosu derived from dendrobium flowers and stems. The results of the analysis revealed 476 metabolites that were differentially expressed between the two types of jiaosu. The outcomes demonstrated that the two jiaosu prepared from stems and flowers had different qualities, with the stem jiaosu having more lignin metabolites and the flower jiaosu having antioxidant and antibacterial qualities.

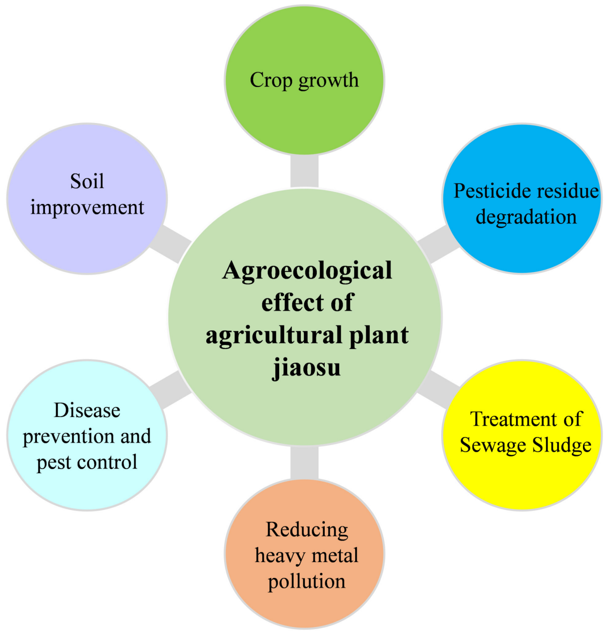

FIGURE 7
Agroecological effect of agricultural plant jiaosu.

7 Agroecological effect

The prolonged use of chemical pesticides and fertilizers can have severe consequences (Tripathi et al., 2020). Issues such as water body eutrophication, heavy metal pollution, increased presence of hazardous compounds, nitrogen oxide emissions, soil compaction, significant reduction in microbial diversity, and concerns over food safety and pest resistance are becoming increasingly prominent. APJ represents a multifaceted system that integrates nutrient components, active metabolites, and beneficial microorganisms. It serves as an ecological product utilizing waste resources from farmland. Due to its versatility, jiaosu is widely utilized as a liquid fertilizer, pesticide, and soil enhancer. The agroecological effects of this study are shown in Figure 7.

7.1 Crop growth

APJ is abundant in beneficial microorganisms, which effectively balance soil microbiota (Montoya-Martínez et al., 2022). Lactic acid bacteria, among them, can inhibit harmful bacteria, manage various crop diseases, and promote the development of a healthy soil microbial environment (Raman et al., 2022). Moreover, the APJ contains essential macro and trace elements that plants can directly absorb and utilize (Kaur et al., 2023). Organic acids within it facilitate the breakdown of insoluble mineral elements into soluble forms, further enhancing plant nutrition (Sharma et al., 2013). APJ serves as a versatile liquid fertilizer for soil irrigation and plant spraying. It is also rich in various plant hormones such as auxin (IAA), cytokinin (CTK), gibberellin (GA), and abscisic acid (ABA), which significantly boost crop photosynthesis and support overall crop growth.

Cheng et al. (2023) set up two treatments of spraying APJ and water to determine the enzyme activities related to stress resistance of Chinese cabbage after 30 days of growth. Through transcriptome, metabolome, and rhizome microbiome analysis, the results showed that APJ did not change the abundance of rhizosphere microorganisms, but improved the diversity of microorganisms, thereby promoting plant growth. The use of APJ can greatly reduce the use of chemical pesticides and improve the quality of the ecological environment.

Xu S. et al. (2023) added 10 % of the APJ to the biogas residue, and the volatile fatty acids and organic substances in the APJ were further decomposed, which significantly improved the plant height, fresh weight, leaf area, and other plant characteristics. Therefore, supplementing APJ can improve the applicability of biogas residue and APJ to agricultural applications. Spraying APJ on the surface of crops can effectively improve the yield and quality of agricultural products, which provides a theoretical basis for subsequent practical production applications.

7.2 Soil improvement

Soil serves as the foundational matrix for plant growth and nutrient delivery, and maintaining a balance among soil, fertilizer, and plants is essential for sustainable agricultural production (Eisenhauer et al., 2017). Prolonged use of chemical fertilizers and pesticides has led to serious soil degradation, including pH imbalance, compaction, and heavy metal pollution. APJ, rich in organic matter and organic acids, possesses an acid-base buffering capacity that can effectively amend soil pH, offering a remedy for soil health.

Pennisi (2016) inoculated the grassland soil into the barren soil to make it "Boostershots" so that the soil changed from barren to fertile. The fundamental reason is that the rich microbial community in the grassland survives and reproduces in the barren land and gradually improves the quality of the soil.

Widmer et al. (2006) also showed that organic planting patterns could change the abundance and structure of soil microflora, and promote the growth and reproduction of beneficial microorganisms while inhibiting harmful microorganisms. A variety of organic acids and enzymes produced by some microbial metabolism can decompose mineral nutrients in the soil that cannot be directly absorbed and utilized by crops and are insoluble and unabsorbable (Arun and Sivashanmugam, 2017).

7.3 Disease prevention and pest control

The pH of mature fermented APJ is typically around 4 (Dai et al., 2020). This acidity is attributed to the presence of beneficial microorganisms, notably lactic acid bacteria, which metabolize to produce organic acids, thereby lowering the fermentation system's pH and inhibiting the growth of harmful microorganisms. Low-grade volatile fatty acids in APJ also inhibit certain pest enzymes, disrupting their normal physiological functions (Agnihotri et al., 2022). Furthermore, plant hormones like gibberellin exhibit synergistic effects in pest management, contributing to effective pest control (Castro-Camba et al., 2022).

Zhang et al. (2020) first studied the characteristics of APJ and its antibacterial activity against Botrytis cinerea. The results showed that APJ was a microbial ecosystem composed of acid-based substances and beneficial microorganisms, which had a good inhibitory effect on Botrytis cinerea and lasted for a long time.

Gao et al. (2022) studied the fermentation characteristics and antifungal activity of the APJ using medicinal plant waste leaf stems as raw materials and Fusarium oxysporum as the target pathogen. The isolation and identification of antagonistic microorganisms of the APJ showed that 47 strains had antagonistic activity against Fusarium oxysporum. The application of APJ significantly reduced the incidence of Fusarium root rot. Ginger and garlic APJ have antagonistic effects on Ralstonia solanacearum. After 2 days of treatment, the diameter of the inhibition zone was 3.0 and 2.2 cm, respectively. Allicin is a natural component that effectively prevents and controls plant diseases (Slusarenko et al., 2008).

In summary, the disease prevention and pest control function of the APJ is due to the organic acids and beneficial microorganisms in the APJ, and the APJ containing aromatic plants with special insect repellent and insecticidal functions such as garlic, ginger, and onion is more effective for pest control. Therefore, in agricultural production, aromatic plants with insect-repellent effects such as garlic, ginger, onion, pepper, and Humulus can be used as substrates for plant disease prevention and pest control.

7.4 Reducing heavy metal pollution

Heavy metal pollution is widespread, mainly through water, air, and soil pollution, which leads to excessive heavy metals in agricultural products (Li et al., 2008). In recent years, news about heavy metal-exceeded foods has been common, and soil is considered to be the main source of heavy metals entering the food chain. At present, microorganisms are mainly used to reduce the availability of heavy metals in soil. The APJ is rich in nutrient-active substances and microbial groups. Applying it to the soil can not only reduce the content of heavy metals in the soil and reduce the migration of heavy metals, to achieve the purpose of improving soil pollution, but also increase the content of organic matter, nitrogen, phosphorus, potassium, and other nutrients in the soil, and increase soil fertility.

Cadmium (Cd) pollution poses a serious threat to various ecosystems. Phytoremediation is an alternative method to promote soil health. Xu Z. G. et al. (2023) mixed Ginkgo biloba leaves, pine needles, and Eucommia bark and fermented naturally to obtain jiaosu and jiaosu residue. The protein, phenols, vitamin E and alcohol contents of jiaosu and jiaosu residue were 4,400 $\pm$ 0.46, 0.22 $\pm$ 0.01, 0.88 $\pm$ 0.24, and 4.63 $\pm$ 0.25 μL/mL, respectively, with good antioxidant activity. Studies have shown that the application of jiaosu and jiaosu slag can improve the properties of cadmium-contaminated soil and promote the cadmium tolerance of plants.

Due to the high toxicity of heavy metals to human health, heavy metal pollution in paddy fields has become a serious problem. Mori et al. (2016) developed a bark plant jiaosu that does not contain chemical substances using bark as a fermentation raw material to inhibit the absorption of cadmium by rice.

7.5 Treatment of sewage sludge

Water pollution, particularly from gray water, is a global concern due to its high COD (Chemical Oxygen Demand) value and richness in phosphorus and ammonia nitrogen (Ghaly et al., 2021). Direct discharge can lead to water and soil eutrophication, which is detrimental to plants. Therefore, it is crucial to treat sewage harmlessly. Studies indicate that the APJ plays a significant role in sewage and activated sludge treatment.

Nazim (2013) found that APJ could completely remove ammonia nitrogen and phosphorus in gray water after 27 days of treatment, and TDS (total dissolved solids), BOD (biochemical oxygen demand), and COD showed a downward trend. Tang and Tong (2011b) also proved that the APJ can effectively remove ammonia nitrogen and phosphorus in sewage.

Rasit and Chee Kuan (2018) showed that the APJ could effectively remove oil, TSS (total suspended solids), and COD in palm wastewater. Studies by the Ministry of Science and Technology of India have shown that the hydrogen production capacity of dairy waste-activated sludge has been greatly improved after the treatment of APJ (Arun and Sivashanmugam, 2018).

Arun and Sivashanmugam (2015a) demonstrated that plant jiaosu had protease, amylase, and lipase activities, which could reduce 37.3 % of total solids, 38.6 % of suspended solids, and 99 % of pathogens in activated sludge of dairy waste. This important result may help researchers to compare the effects of plant jiaosu on the treatment of industrial sludge with various physical and chemical pretreatment methods to improve the biogas production of sludge digestion devices.

7.6 Pesticide residue degradation

Pesticide residue is a significant issue affecting food safety. Zhang F. et al. (2013) showed that organophosphorus pesticide residues in whole wheat plants (290 μg/g) and corn (270 μg/g) in Hohhot were much higher than those in agricultural soils (185 μg/g). Pesticide residues in these crops not only seriously affect the quality of vegetables, but also can be transmitted along the food chain and food web, and ultimately into the human body, endangering human health. Moreover, Azizi and Homayouni (2009) studied the degradation of diazinon and malathion by lactic acid bacteria during vegetable fermentation. They pointed out that the extracellular enzymes of lactic acid bacteria can degrade diazinon which is sensitive to hydrolytic activity and low pH conditions, and the isolated lactic acid bacteria have a much stronger ability to decompose pesticides and reduce pH in mixed culture.

8 Challenges of the moment

The APJ industry benefits from the application of biotechnology in agriculture in several ways, including increased crop growth, improved plant stress resistance, and less use of chemical pesticides and fertilizers (Mahanty et al., 2017). However, as it develops, it must also overcome several obstacles, chief among them being the following:

1. Lack of normalization and standardization: the production of APJ lacks consistent norms or standards. Variations in active substances and their efficacy among different producers impact the stability and reliability of product effects, leading to inconsistent product quality.

2. Inadequate research on the mechanism of action: APJ is known to enhance soil and encourage plant growth (Pahalvi et al., 2021), but a more thorough study is needed to determine the precise mechanism of action, such as the dynamic shift of the microbial community or the precise relationship between enzyme activity and crop physiological response, to guide application in a way that is supported by science.

3. Optimization of application technology and method: currently, a pressing technical challenge is determining the optimal application method, dosage, and timing tailored to different crop types, soil conditions, and climatic variables to maximize yield increase and economic benefits.

4. Ongoing R&D and innovation: the APJ industry is poised for growth driven by increasing demand for sustainable agricultural practices. Continued investment in research and development, coupled with technological innovation, is crucial for developing new and effective strains, optimizing fermentation processes, and achieving sustainable agricultural development.

To address these challenges and foster the healthy development of the APJ industry, collaboration among government entities, scientific research institutions, businesses, and farmers is essential. This collaboration should focus on improving standardization, enhancing market supervision, increasing investment in scientific research, and providing robust policy guidance.

9 Future outlook

With the issuance of multiple papers in recent years, the advancement of ecological agriculture has become the prevailing trend. Jiaosu, an agricultural plant, is a type of fermentation broth made from plants. Its features include broad applicability, low cost, easy operation, and green environmental protection (Gao et al., 2022). This trend aligns with the advancement of contemporary ecological agriculture and supports the robust growth of the agricultural environment. The researcher's attention should be directed toward it. Due to a dearth of fundamental research, agricultural plants like jiaosu are still relatively new. The following observations are made in this review:

1. The primary impetus behind ecological agriculture: APJ is thought to be a useful instrument for advancing the growth of ecological agriculture. Obtaining native beneficial microorganisms in the area can help meet the development requirements of sustainable agriculture while also enhancing soil biological activity and promoting a healthy cycle of microorganisms in the soil-plant system (Montoya-Martínez et al., 2022). This reduces the need for chemical fertilizers and pesticides and enhances the utilization of waste as a resource.

2. New methods for getting rid of waste: the use of APJ in garbage disposal will receive increasing attention as environmental consciousness grows. Microbial fermentation technology has the potential to transform agricultural waste into a valuable biological fertilizer, facilitating resource recycling and mitigating environmental pollution (Bala et al., 2023).

3. Product diversification and technological innovation: the production technology of APJ will be continuously optimized with the advancement of research and technology. This may involve screening and applying new strains, improving the fermentation process, and other measures to meet the unique requirements of various crops and soil types. Additionally, a wider range of products will be offered to better suit the requirements of various agricultural production chains.

4. Simple to use and promote: APJ technology is easy to promote in large rural areas due to its straightforward qualities and capability to turn trash into treasure. This helps to boost small farmers' productivity, encourage agricultural efficiency, and raise farmers' income.

5. Encouraging the health of agricultural ecosystems: to sustain and increase the stability and productivity of the overall agricultural ecosystem, long-term use of APJ is anticipated to improve soil structure, enhance soil water and nutrient retention capacity, promote root growth, and improve crop stress tolerance (Wang et al., 2024).

10 Recommendations

The following ideas might be put up to further encourage the application and advancement of APJ in light of the knowledge gathered from this review:

1. Fermentation process optimization: to increase the effectiveness and caliber of APJ production, more studies should be done on fermentation conditions optimization. This entails creating standardized procedures and investigating cutting-edge fermentation methods.

2. Economic feasibility: to determine if producing APJ is economically feasible, cost-effective methods for acquiring and processing raw materials are investigated. Working together with businesses can assist cut expenses and increase output.

3. Regulatory framework: to guarantee the security and effectiveness of APJ production and use, clearly define regulatory norms and guidelines. This will help farmers and other stakeholders use it widely.

4. Public education and awareness: raising public knowledge of the advantages of APJ can help these products find a larger market and garner more support. Adoption of APJ in agricultural techniques can be encouraged by consumer and farmer education initiatives.

5. Collaborative research: to hasten the development and implementation of APJ technologies, collaboration in research is encouraged amongst academic institutions, governmental organizations, and the commercial sector. This multidisciplinary approach may result in quicker implementation and more creative solutions.

11 Conclusion

The goal of this study is to present a thorough analysis of the present classification, procedures, makeup, agricultural uses, and difficulties related to APJ. The study also examines new developments in the fields of microbial fermentation, fermentation processes, mechanisms, and raw material selection. The main objective is to elucidate the capacity of APJ to promote sustainable agriculture practices and strong soil-microbe-plant agro-ecosystems. This study concludes that using organic waste to prepare APJ is practical and delivers significant benefits to the environment and the economy through a systematic evaluation of the literature and data analysis. High-quality APJ can be efficiently generated, lowering environmental pollution and improving resource recycling, by using acceptable microbial fermentation processes and appropriate organic waste as raw materials. Even though APJ can be used to treat organic waste in the current technological environment, there are still certain technical and financial challenges to be solved, like maximizing the conditions for fermentation, keeping costs under control, and attaining large-scale industrial production. Utilizing APJ for organic waste management greatly advances sustainable agricultural growth and yields a host of environmental advantages, such as better soil quality, increased plant resistance, a decrease in the usage of chemical pesticides and fertilizers, and a reduction in environmental pollution. Additionally, APJ promotes the development of robust soil microbial communities, which supports the long-term viability of agricultural ecosystems.

To ensure that crops grow normally and increase yields per unit area, pesticides are crucial in contemporary agriculture for preventing and managing diseases, pests, and crop damage. On the other hand, persistent misuse of chemical pesticides has seriously jeopardized human health and severely contaminated the environment. Biopesticides have garnered a lot of attention as people's awareness of health, the environment, and food safety has grown. China has been promoting and using APJ, a kind of biopesticide, extensively in recent years. The "green and environmentally friendly" idea is supported by the process of fermenting inferior fruits into jiaosu, which also offers a practical solution to the issues of wasted inferior fruits and resource reuse. APJ will be dependent on environmental protection principles, technological innovation, and the demands of green agriculture in the future. These factors will allow for the continuous optimization of product performance, the expansion of application ranges, and the achievement of sustained industry development and progress through improved supply chain collaboration.

Author contributions

YW: Conceptualization, Data curation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. JL: Data curation, Supervision, Writing – review & editing. XL: Project administration, Validation, Writing – review & editing. SW: Validation, Writing – review & editing. WS: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing. PL: Conceptualization, Methodology, Supervision, Writing – review & editing.

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Conflict of interest

JL was employed by Guizhou Guotai Liquor Group Co., Ltd. XL was employed by Tianjin Research Institute of Industrial Microbiology Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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