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Agricultural waste-based lactic acid production by the fungus *Rhizopus oryzae:* a tool for sustainable polylactic acid production for agricultural use – a review

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Abstract: Lactic acid has gained considerable attention globally due to its multi-purpose application. Commercial lactic acid production uses the fungal species *Rhizopus oryzae*, which produces other organic acids. A crucial point of effective fungal organic acid production is matching the fungal strains' requirements, where the carbon source plays a major role. The highest production rate is achieved when glucose is used as a carbon source. Alternatively, we can apply carbon-rich agricultural residues as carbon sources. Using agricultural waste for lactic acid production provides a sustainable and cost-effective feedstock but also helps to reduce greenhouse gas emissions by diverting waste from landfills and decreasing reliance on fossil fuels. Moreover, polylactic acid (PLA) produced from lactic acid monomers can occur in numerous agricultural applications. We should delve deeper into sustainable methods of using carbon residues to recycle waste, foster the circular economy, and advance sustainable agriculture. Therefore, there is a need for further research on the commercial use of agricultural and food industry wastes for lactic acid production.

Keywords: biochemical process; biotechnology; fungi; organic acids

Lactic acid, the so-called "milk acid," is important in several biochemical processes. Agrochemicals, pharmaceuticals, cosmetics, and food industries can utilise lactic acid and its derivatives. The use of lactic acid extends beyond the laboratory, as it is a vital chemical commodity with broad applications in various industries such as food, textile, chemical, and pharmaceutical. Because of its inherent moisturising and antimicrobial properties, lactic acid has numerous applications in producing hygienic compounds (more effective antibacterial agents than malic, citric, propionic, and acetic acids) and personal care products, catering to health and beauty needs. This underscores the versatility of lactic acid and its significance in developing various consumer products (Coban and Demirci 2016). Market research predicts the global lactic acid market will reach 9.8 billion US dollars by 2025 (Acedos et al. 2022). Food and food-related applications use approximately 70% of the total lactic acid. Produced from renewable carbohydrates, lactic acid has the potential to become a substantial commodity-chemical intermediate, serving as a feedstock for biodegradable polymers, oxygenated chemicals, plant growth regulators, environmentally friendly "green" solvents, and chemical intermediates (Jin et al. 2005, Kozlovskiy et al. 2017).

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Organic acids are the natural products of many biological processes. For instance, plant roots exude organic acids, which lead to rhizosphere acidification and mineral weathering, contribute to protons, and act as ligands for complex metals (Richter et al. 2007, Paul et al. 2021). Microbial metabolism also produces organic acids, primarily through oxidative respiration or fermentation, using glucose as a carbon source (Kalayu 2019). The amounts and types of organic acids produced differ with different organisms, and the solubilisation efficiency depends on the acid's strength and nature. However, we can also use lignocellulosic agricultural residues consisting of complex carbohydrates to synthesise organic acids. In this case, first hydrolysis of these constituents to the simple sugars is necessary, followed by microbial fermentation, producing organic acid. Chemical processes like applying diluted acids hydrolyse the lignocellulosic materials (Eiteman and Ramalingam 2015). On the other hand, amylolytic fungal cultures like *Rhizopus oryzae* (also known as *Rhizopus arrhizus*) can produce lactic acid from various starch-based materials without saccharification, allowing for the application of the "simultaneous saccharification and fermentation" approach for the fermentation of starch waste materials (Jin et al. 2003).

Soil fungal hyphae can grow deeper into the soil than bacteria; soil fungi are important for breaking down inorganic phosphate because they make more acids than bacteria (Alori et al. 2017). Acids like gluconic, citric, lactic, 2-ketogluconic, 2-oxogluconic acid, tartaric, and acetic acid are just a few examples. Previous studies have shown that the fungal species *R. oryzae* can mainly produce two organic acids, L(+)-lactic acid and fumaric acid (Naude and Nicol 2017, Zain et al. 2021). Therefore, researchers are conducting extensive studies on producing organic acids, ethanol, enzymes, and other commercially intriguing compounds by *R. oryzae*. The fungus *R. oryzae* offers a beneficial bio-based green organic acid production system as an alternative to chemical-based industrial modes, which often cause chemical hazards and pollution. This demonstrates the unique potential of the commercial production of lactic acid.

Wee et al. (2006) published a comprehensive review that discussed the principles and mechanisms of lactic acid biosynthesis, described lactic acid-producing microorganisms, discussed substrates for lactic acid, and explored various applications of lactic acid. Among the potential applications, producing polylactic acid (PLA), a polymer with a wide range of future applications, received particular attention. According to Ali et al. (2023) and the International Union of Pure and Applied Chemistry, biological activity can degrade biodegradable plastics, macromolecular substances that reduce molecular weight. However, not all bioplastics degrade, and many require specific conditions, such as elevated temperature and enhanced microbial activity during composting, for their degradation to occur. Lactic acid monomers synthesise polylactic acid, a biodegradable polymer that can be an eco-friendly replacement for petroleum-based plastics (Coban and Demirci 2016). PLA can be synthesised by reusing agricultural and food industry waste materials. Swetha et al. (2023) recently stated and reviewed a link between the cost-effective production of PLA and the utilisation of agricultural and food waste for lactic acid production. However, PLA bioproduction still needs more progress to be comparable to PLA chemical production. Therefore, this review aims to present some suitable examples of agricultural and food waste use for lactic acid production, followed by the use of PLA for reasonable agricultural use, and identify potential knowledge gaps for further research.

RHIZOPUS ORYZAE, AN ORGANIC ACID-PRODUCING FUNGUS

R. oryzae is a ubiquitous filamentous fungus that thrives on decaying organic matrix. Taxonomically, it belongs to the class Phycomycetes, order Mucorales, family Mucoraceae, genus *Rhizopus*. The species *R. oryzae* is a saprophytic, heterothallic microfungus that requires a simple ecosystem to survive, is fast-growing (1.6 mm per hour), and can grow vigorously between 25 °C and 45 °C. These fungi are typically found in soil, decaying fruit, vegetables, and animal faeces. These characteristics make them almost ubiquitous in nature, allowing the colonisation of almost all plant material. The U.S. Food and Drug Administration (FDA) classifies the species *R. oryzae* as GRAS (Generally Recognised As Safe), allowing its use for human consumption within the United States. However, the European Food Safety Agency (EFSA) does not consider filamentous fungi as QPS (Qualified Presumption of Safety). This makes people worry about safety and means that mycotoxins must be checked in each European product (Cantabrana et al. 2015, Herman et al. 2019).

R. oryzae can grow on various carbon sources such as glycerol, ethanol, sugars, fatty acids, and oils (Meussen et al. 2012, Dulf et al. 2018, Dhandapani

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et al. 2021). The industry uses different *Rhizopus* species for submerged fermentation and biotransformation to produce various products. There are enzymes (lipase, protease, glucoamylase, and cellulolytic enzymes), organic acids (lactic acid, fumaric acid, malic acid, itaconic acid, and succinic acid), steroids, terpenoids, alkaloids, phenolic compounds that can act as antioxidants, flavour compounds (D-limonene), pesticides, and herbicides (Uyar et al. 2010, Ezeilo et al. 2020, Rivera et al. 2023). According to Londoño-Hernández et al. (2017), we can use *R. oryzae* to produce fermented foods like tempeh. *R. oryzae* produces more lactic acid than any other organic acid. It became famous for making much lactic acid even when no oxygen was present, making it a useful organism for making this compound in factories. Bai et al. (2008) highlighted that lactic acid bacteria use an enriched medium to produce current industrial lactic acid. However, the main benefits of using *R. oryzae* include its exclusive formation of the L-isomer and simple nutritional requirements. Scientists are also looking into how *R. oryzae* could be used in bioremediation because it can break down pollutants like pentachlorophenol and polycyclic aromatic hydrocarbons (Ma et al. 2016, Ruiz-Lara et al. 2020).

Factors influencing the production of lactic acids by *Rhizopus oryzae*

The ability of *R. oryzae* to increase the production of organic acids mostly depends on things like the type of fungus, the availability of nutrients (carbon and nitrogen sources), the temperature, the pH, the time of incubation, the amount of oxygen present, and the culture conditions. Selection of a particular fungal strain is also an important factor. Several studies, such as Tay and Yang (2002), Thongchul et al. (2010), Göçeri et al. (2021), Zain et al. (2021), and Rodriguez-Torres et al. (2022), have used the strain *R. oryzae* NRRL 395. Researchers have proven that this strain can produce lactic acid from both commercial and agricultural residual carbon sources, particularly emphasising the sustainable use of agricultural waste phytomass.

Temperature. Temperature is one of the most important physical parameters influencing the metabolic rate and amount of the end product (Maslova et al. 2019). It plays an important role in the production of lactic acid by affecting the activity of enzymes (Dhandapani et al. 2021). Understanding the optimal temperature range for the growth and metabolism of different microorganisms is crucial in these fields, as it can help to optimise production processes and ensure the safety and quality of the final products. Previous research reports (Trakarnpaiboon et al. 2017, Dhandapani et al. 2021, Zain et al. 2021) suggested that temperature is a major factor impacting lactic acid fermentation. Bulut et al. (2009) studied seven different temperatures from 22.5 °C to 40 °C and found the optimum temperature of 32.5 °C for the maximum lactic acid production. However, lactic acid production was stable in the temperature range between 27.5 °C and 32.5 °C.

Dhandapani et al. (2021) observed a proportional increase in lactic acid production with increasing temperature, reaching a maximum yield of 21.3 g/L at 40 °C. Low temperatures favour saccharification, while high temperatures favour fermentation (Dhandapani et al. 2021). The temperature of 40 °C could be considered the upper limit for saccharification and the lower limit of the temperature range favouring fermentation (Dhandapani et al. 2021). Above 40 °C, we observed a sharp decline in acid production, which decreased by almost 15.4% when we maintained the operating temperature at 44 °C. The thermal inactivation of cellulase active sites causes a loss in activity, which explains the poor transformation (Dhandapani et al. 2021).

pH value. In the fermentation process of making lactic acid with fungal cells, fungi can handle high concentrations of lactic acid when the medium pH is lower than bacteria (Matsumoto and Furuta 2018). Based on the findings of Uyar et al. (2010), it seems that *R. oryzae* secretes significant amounts of lactic acid into the growth media, which leads to a decrease in pH. *R. oryzae* can also survive in a wide range of pH values, from 4.5 to 7.5 (Ibarruri and Hernández 2018). These authors investigated mycelium formation under different pH conditions (3.4–5.6), observing higher mycelium formation under acidic pH values (3.4–4.5). Usually, NaOH or $CaCO_3$ (Bai et al. 2008, Ren et al. 2014, Ma et al. 2020, Zain et al. 2021) are used to maintain the pH during fungus culturing.

The acid production caused the pH values in the reactor to drop. Soccol et al. (1994) observed a significant decrease in pH from an initial value of 6.9 to a final value of 4.8 in a glass column reactor during lactic acid production. Furthermore, the pH value influences the proportion of acids the fungi produce. Roa Engel et al. (2011) showed that *R. oryzae* fumaric acid production decreased as the medium's pH decreased from 5.0 to 2.4. Ren et al. (2014) and

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Aziman et al. (2015) reported that at higher pH values (pH 6), more lactic acid production occurred. They explained that higher lactate production is due to reaction equilibrium breakdown and fungal morphology change during fermentation at a higher pH.

Nutrient supply. Nitrogen supply substantially affects microbial growth and extracellular enzyme production (Di Lonardo et al. 2020, Zhao et al. 2021). Researchers recommend limited nitrogen levels in the culture medium for lactic acid production in conventional cultures of *R. oryzae* (Taherzadeh et al. 2003, Yu et al. 2007). For instance, Thongchul et al. (2010) confirmed that treating the cassava pulp hydrolysates with extra organic nitrogen improved cell growth and ethanol production while reducing lactic acid production. Several authors have said that ammonium sulphate and other inorganic nitrogen sources work better than ammonium nitrate, urea, yeast extract, peptone, and corn steep liquor for making lactic acid by fungi (Yin et al. 1997, Jin et al. 2003, Ren et al. 2014). For *Rhizopus* sp., the best amount of ammonium sulphate to use in the culture medium to make lactic acid was between 1.0 and 4.0 g/L (Marták et al. 2003, Miura et al. 2003, Park et al. 2004, Maas et al. 2006, Taskin et al. 2013, Zain et al. 2021, Zaveri et al. 2022). Similarly, ammonium chloride (N concentration of 3.5 g/L) was confirmed as an effective nitrogen source for lactic acid production (Ren et al. 2014).

Phosphorus is one of the nutrients that affect *R. oryzae*'s biochemical processes. The types and concentrations of organic acids produced by rhizospheric fungi vary according to the source of available phosphorus. Regarding general soil fungi, medium supplementation with calcium phosphate led to the highest proportion of gluconic acid production, whereas medium supplementation with the other phosphorus (P) sources (aluminium phosphate or phosphorite) caused the highest proportions of citric and valeric acid production (Scervino et al. 2010). Evidently, organic acid production can depend on the phosphorus forms applied.

UTILISATION OF AGRICULTURAL RESIDUES AS CARBON SOURCES FOR LACTIC ACID PRODUCTION

The type of carbon source plays a key role in producing organic acid by fungi (Dörsam et al. 2017). The fungi can get their carbon from commercial sources like glucose, xylose, sucrose, and starch, which break down quickly, or carbon-rich agricultural wastes like corn powder, rice powder, potato starch, paper sludge, and cassava pulp. Alternatively, carbon sources such as crude glycerol derived from the biodiesel industry can be utilised (Vodnar et al. 2013). Researchers have studied improving organic acid production by controlling various factors and medium components. Generally, *R. oryzae* converts glucose to lactic acid under aerobic conditions, whereas ethanol production increases under anaerobic conditions. Other reports of lactic acid production from starch and xylose exist. Given the cost-effective approach, agricultural residues, including solid agro-industrial wastes, are currently receiving attention for their potential to produce organic acids such as lactic acid and fumaric acid (Thongchul et al. 2010, Göçeri et al. 2021).

Göçeri et al. (2021), Wang et al. (2009), and Maas et al. (2006) reported that glucose is the most favourable carbon source for lactic acid production by *R. oryzae*. In a mineral medium with glucose as the only carbon source, *R. oryzae* can make L(+)-lactic acid that is optically pure (Maas et al. 2006). Microbial strains can convert xylose (pentose sugar) into lactic acid under aerobic conditions through the pentose phosphate pathway. Interestingly, *R. oryzae* can make lactic acid from xylose instead of glucose, which most fermentation processes use (Zheng et al. 2016). In 2006, Maas et al. (2006) did a study using xylose in commercial media to see how different strains of *R. oryzae* could make lactic acid. They got yields of 470 to 710 g/L. The authors also examined the differences between glucose and xylose as carbon sources. They found that using xylose at levels higher than 40 g/L stopped substrates from being used, leading to slower lactic acid production rates. Moreover, fermentation was 4.5 times longer when xylose was used as a carbon source (Maas et al. 2006).

Starch is a complex carbohydrate. It consists of two types of polysaccharides: amylose and amylopectin. *R. oryzae* can use starch as a carbon source for lactic acid production through fermentation. During fermentation, the fungi break down starch into simpler sugars (such as glucose), which subsequently metabolises into lactic acid (Akoetey and Morawicki 2018). In a rotating bed fermenter, Tay and Yang (2002) immobilised *R. oryzae* cells in cotton cloth to produce lactic acid using corn starch and glucose as carbon sources. These authors obtained 100% (*w*/*w*) and 90% (*w*/*w*) lactic acid production using cornflour and glucose as substrates, respectively. However, many starch-containing materials remain

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as waste from agricultural crop processing and the food industry despite their potential for reuse.

Waste materials have the potential to serve as valuable raw materials for the production of various valuable products, including bioethanol, biogas, biodiesel, organic acids, enzymes, and microbial biomass. The literature has extensively discussed and reviewed these aspects (Mladenovic et al. 2016). According to these authors, wastes and by-products from the agriculture and food industries, such as whey, molasses, distillery stillage, waste starch, and lignocellulosic materials, are a good source of fermentable sugars and many other substances of great importance for the growth of microorganisms, such as proteins, minerals, and vitamins. Using these wastes as feedstocks for cultivating bacteria and fungi could be considered a reasonable re-use of these materials, a way to dispose of them responsibly, and a way to reduce production costs. Panesar and Kaur (2015) have already reviewed the potential utilisation of waste from agriculture and the food industry. Panesar and Kaur (2015) listed a multitude of potential fermentation sources, including wastes or by-products from agricultural product processing (fruit and vegetable peels/waste, corncob, etc.) and field residues left in an agricultural field after crop harvest (stalks, stems, leaves, seed pods). Additionally, lactic acid production from food processing waste is gaining attention now (Ibarruri and Hernandez 2019, Salvanal et al. 2021).

Many microorganisms can use agricultural wastes and by-products as substrates to produce lactic acid. For instance, locally isolated bacteria can biosynthesise lactic acid using waste-based substrates like sisal stems (Muruke et al. 2006). However, most published studies focus on the fungal ability to produce lactic acid, and *R. oryzae* belongs to the obvious fungal species. Ranjit and Srividya (2016) looked at how much biomass and lactic acid *R. oryzae* produced when it was grown on waste-based substrates like rice bran, wheat bran, rice starch water, tea waste, sugar cane bagasse, groundnut, and coconut oil cakes compared to when it was grown traditionally using starch. The sugar cane bagasse showed the highest lactic acid yield. Researchers Groff et al. (2022) and Bai et al. (2008) also documented the effective use of corncobs and grape stalks as the substrate for *R. oryzae* cultivation to generate lactic acid efficiently. Table 1 summarises several typical examples of waste utilisation for lactic acid production. Not only the different waste materials used but also the different reactor types and cultivation conditions contribute to the differences in the effectivity of lactic acid production. Therefore, the variability of the results presented in Table 1 is not only due to the substrate but also due to differing experimental parameters in the individual experiments.

Yu and Hang (1989) used different types of dried cereal biomass (barley, corn, oats, and rice) and cassava powder as substrates to produce lactic acid by *R. oryzae*. The yield was greater in the case of rice, corn, and cassava powder compared to oats and barley as carbon sources. Acid production decreased from 10% to 15% as the substrate (rice) concentration increased. Using carrot processing solid waste as a substrate for *R. oryzae* led to a 55% yield of lactic acid (Garg and Hang 1995).

Thongchul et al. (2010) used hydrolysed cassava pulp by *R. oryzae* to produce lactic acid. However, the primary products from the hydrolysed cassava pulp, with less lactic acid production, were cell biomass and ethanol. *R. oryzae* has also used rice straw as a carbon source for lactic acid fermentation (Chen et al. 2018). However, *R. oryzae* only produced a small amount of lactic acid when it consumed the glucose in rice straw-derived hydrolysates (Chen et al. 2018). In this context, Zhang et al. (2016) identified carbohydrate and lignin degradation products in corn cob and stover hydrolysates (furans, weak acids, phenolic compounds, including syringaldehyde and *trans*-cinnamic acid) as potential inhibitors of lactic acid biosynthesis and recommended removing them from the hydrolysates. Chen et al. (2018) also confirmed increasing lactic acid production after removing polyphenols from the rice straw-derived hydrolysates. Recently, Göçeri et al. (2021) used 100% wheat wastewater as a substrate and found maximum lactic acid production (5.64 g/L).

Dhandapani et al. (2021) used paper sludge as a carbon source to produce lactic acid from *R. oryzae*. The authors found higher lactic acid yields at the substrate concentrations of 75 and 100 g/L and lower yields at 50 g/L. However, they observed a high initial production at a concentration of 100 g/L, followed by a slow and stable production over time. Dhandapani et al. (2021) presented an improvement in lactic acid production from paper sludge. These authors developed a simultaneous saccharification and fermentation method using an optimised cellulase cocktail to maximise the lactic acid yield. Similarly, Jie and Zhang (2008) confirmed *R. oryzae*'s good ability to produce lactic acid from fibre waste

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Table 1. Examples of the utilisation of various wastes from agriculture and food industry for lactic acid production regardless of the reactor type and incubation parameters

Substrate used	Lactic acid production/conversion rate	Reference
Oat flour	51.7 g/L	Koutinas et al. (2007)
Sweet potato Scum	38.49 ± 0.51% (*w*/*w*)	Ge et al. (2008)
Bagasse	max. 28.45%	Cui et al. (2018)
Inedible cassava starch and leaves	0.95 g/g	Azmi et al. (2016)
Yam peel hydrolyzate	80.03% and 75.63% for the surface and submerged fermentation, respectively	Ajala et al. (2021)
Wheat wastewater	5.804 g/L at the 1.0 × 10^6 spores/mL	Göçeri et al. (2021)
Corncob hydrolysate	355 g lactic acid per kg corncobs	Guo et al. (2010)
Wastewater from an industrial starch plant	450 g/kg (*Rhizopus arrhizus*)	Huang et al. (2003)
Seafood processing waste	0.723 g/L/h (30 g/L of exogenous glucose added)	Huang et al. (2007)
Potato, corn, wheat and pineapple waste	650–760 g/kg	Jin et al. (2005)
Corncobs	299 g per kg dry matter of corncobs	Ruengruglikit and Hang (2003)
Wheat straw powder	230 g/kg	Saito et al. (2012)
Pretreated dairy manure	1 210 mg/L and 40.09%	Sun et al. (2012)
Molasses and chicken feather protein hydrolysate	38.5 g/L	Taskin et al. (2012)
Loquat kernel flour	45.4 g/L	Taskin et al. (2013)
α-Amylase-treated liquefied cassava starch	83.7 g/L	Trakarnpaiboon et al. (2018)
Potato peel waste	39 g/kg (optimised for ethanol as the major product)	Uyar and Uyar (2023)
Zizania latifolia waste and cane molasses	129.47 g/L	Yin et al. (2023)
Potato starch wastewater	850–920 g/kg	Huang et al. (2005)

from the alkaline antraquinone (NaOH-AQ) pulping process (i.e., from the production of wood pulp using NaOH and antraquinone).

Furthermore, the incubation conditions will play an important role in effective lactic acid production. An experiment about making fumaric acid by fermenting apple pomace ultrafiltration sludge and apple pomace by *R. oryzae* found that 72 h was the best time to let it grow (Das et al. 2015). Zain et al. (2021) and Aziman et al. (2015) also reported the highest lactic acid production after 72 h of incubation from the solid pineapple waste substrate. Ren et al. (2014) reported maximum lactic acid production occurring after 96 h, followed by a decrease of it. Bulut et al. (2009) monitored the rate of lactic acid production within a period of 245 h. The authors observed the highest lactic acid concentration at 105 h, followed by a slight decrease over time.

Much recent research (Lian et al. 2020, Sadaf et al. 2021, Cao et al. 2022) focuses on agricultural waste phytomass (which has carbs, starch, cellulose, whey, and molasses) rather than commercial carbon sources for making lactic acid (Göçeri et al. 2021). Agricultural wastes are abundantly available and commercially feasible. This is one of the best bio-based options for sustainable agricultural waste phytomass management to convert waste to valuable products through a carbon-neutral approach. On the one hand, this technology provides a zero-waste strategy; on the other, it represents a tactic for waste recycling. Generally, the various characteristics and properties of agricultural wastes hinder the identification of optimal conditions for lactic acid production. For the potential improvement of the lactic acid production efficiency, various pre-treatments of the waste materials were tested, such as thermal or chemical measures, to facilitate the enzymes to access and decompose the cellulose (Ranjit and Srividya 2016).

Additionally, some fermentation procedures can produce valuable waste that could be reasonably

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used. For instance, Ma et al. (2020) applied *Sophora flavescens* residues, frequently used in Chinese traditional medicine, as a carbon source for lactic acid production. As a result, the solid residues after fermentation represent protein- and micronutrient-rich products potentially useful as animal feed additives. Researchers have extensively investigated the potential use of fungal biomass, a by-product of lactic acid production, as an animal feed or feed additive (Ibarruri and Hernández 2019).

POLYLACTIC ACID AND ITS UTILISATION IN AGRICULTURE

Taib et al. (2023) talked about two main ways to make PLA from monomers: ring-opening polymerisation and polycondensation, both of which use metal or organic catalysts to speed up the process. PLA is a promising bio-based alternative to fossil-derived plastics in various applications in agriculture and the food industry, including food packages that have been proven to maintain nutritional values (Seglina et al. 2010), nonwoven vegetation blankets, hydrogels that can enhance soil retention capacity (Paswan et al. 2022), biodegradable plastic mulches (Hsieh et al. 2017, Cacciotti et al. 2018, Ju et al. 2021), and nanocomposites for the remediation of pesticide-polluted wastewater (Behrooz et al. 2023). Recently, Serna-Abascal et al. (2022) reviewed more than 50 examples of the potential use of biodegradable polymers in agriculture, predominantly as coatings for the controlled release of fertilisers, hydrogels for the improvement of soil retention capacity, foams, pellets for various uses, and so on.

Ali et al. (2023) recently looked at how biodegradable PLA might be. They found that it depends on the polymer structure, the environment, ultraviolet radiation, temperature, pH, the community of microbes, and the activity of enzymes. Narancic et al. (2018) observed poor biodegradation ability in the aquatic environment. Researchers tested various additives, including polyethylene glycol and acetyl-tri-n-butyl citrate, to enhance the hydrophilicity of PLA, observing effective biodegradation under composting conditions (Arrieta et al. 2014). Thus, PLA is a compostable bioplastic (Kale et al. 2007).

One possible agricultural application for PLA is the production of tomato yarns from bio-based polymers. In this case, PLA showed physical-mechanical properties comparable to traditional plastics such as polyethylene and polyvinyl chloride (Râpa et al. 2011). Maraveas (2020) reviewed various agricultural applications of biodegradable polymers, including PLA as protective nets for shading, antihail, anti-insects, and windbreak purposes. Agriculture typically uses various outdoor sensors to measure environmental and climatic variables, such as environmental pollution, weather conditions, or nutrient status. In this instance, researchers are testing 3-D printed radiation shields made of PLA to safeguard these sensors (Botero-Valencia et al. 2022).

Biodegradable polymers, such as PLA, are important and reasonable for coating fertilisers to achieve their slow release in the soil (Devassine et al. 2002); researchers have been investigating and testing these applications for more than two decades. Tan et al. (2021) presented a novel method that involves fabricating nanoscale slow-release urea fibre materials through coaxial electrospinning, which encapsulates urea inside polylactic acid fibres. This material showed a slow release of urea up to 84 days. Yuan et al. (2023) introduced an interesting biodegradable composite hydrogel through chemical cross-linking synthesis using gelatine, chitosan, and PLA as raw materials. The solution immersion method can load urea into this material for use in the preparation of slow-release fertilisers.

The possible application of PLA to replace fossil-derived plastics used as mulches with biodegradable plastics has been frequently investigated, where PLA plays an important role. However, a deeper investigation into the fate of PLA-based mulches in soils is necessary to understand their biodegradability and their interaction with the soil biota. The degradability of potentially biodegradable mulches, such as PLA, depends strongly on the climatic conditions (Li et al. 2014). Moreover, Ju et al. (2021) observed different microbial compositions and community structures in the soil treated with biodegradable mulches compared to the classic polyethylene mulch. Ji et al. (2024) thoroughly tested composite materials, such as PLA hyperbranched cellulose nanocrystal composite mulch, to improve the properties of biodegradable mulch. Thompson et al. (2019) tested biostimulants such as biocatalyst products, microbial inoculants, and yard-waste compost extract.

However, biobased mulch films made from PLA could pose a risk to cultivated crops. For example, Reid et al. (2022) reported a reduction in soil nitrate, followed by a reduction in sweet corn yield in the treated low-fertility soil. In this case, She et al. (2024) saw changes in the denitrification pathways in soils exposed to

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different plastics. Using PLA made the dissimilatory nitrate reduction process stronger. They thought the high bioavailable C/NO_x – ratio from biodegradable plastics breaking down would help the dissimilatory nitrate reduction to ammonium (DNRA) bacteria do their job better than the denitrifiers. These processes, in turn, facilitated the retention of ammonium in soils. Therefore, further research is needed to elucidate the potential adverse effect of the PLA in mulch films, and reasonable measures to mitigate these negative effects should be applied in such cases.

FUTURE PERSPECTIVES OF POLYLACTIC ACIDPRODUCTION AND APPLICATION

For future studies, we suggest investigating the economic and sustainable feasibility of organic acid production from various agricultural wastes and possibilities to scale up production. To meet the requirements of mass production, the waste phytomass must be abundant, easily obtainable, and inexpensive. The rate of acid production (g/L/h) and the rate of carbon conversion to lactic acid (%) should be examined to understand how to move the process from the lab to the production of organic acids on a large scale.

According to Ju et al. (2021), the increased occurrence of pathogens and degradation microbial species in soils treated with PLA and other biodegradable polymer-based mulches compared to polyethylene poses a potential risk to crops and human health. Moreover, Zhang et al. (2018) documented that earthworms can ingest weathered biodegradable plastics, unlike traditional plastics like polyethylene. Therefore, further research is necessary to investigate the potential impact of PLA and other biodegradable plastics and the potential degradation by-products on edaphic organisms.

Traditional chemical additives can enhance the mechanical properties of biobased plastics but limit their sustainability (Maraveas 2020). Therefore, environmentally friendly bioplastics based on PLA should either be free or contain a minimal amount of these additives to maintain a negligible environmental impact. For instance, we can use spent coffee grounds extract as an antioxidant, replacing traditional antioxidative agents for stabilising traditional plastics (Cacciotti et al. 2018). Similarly, França et al. (2019) suggest using the finely ground shells of *Orbignya phalerata* nuts as a low-cost filler with antioxidant activity for PLA-based mulch.

It is necessary to consider Swetha et al. (2023) statements concerning the possible environmental pollution due to PLA production from renewable sources. The production process requires fossil fuels to generate electricity, emits greenhouse gases, and has the potential to pollute water bodies, among other issues. Further research should consider these aspects to ensure a fully sustainable and environmentally friendly re-use of agricultural and food industry wastes and by-products.

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