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Review

Underutilized Malaysian Agro-Industrial Wastes as Sustainable Carbon Sources for Lactic Acid Production

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Abstract: Lactic acid is a versatile chemical with a wide range of industrial applications, including food additives as well as the production of biodegradable plastics, pharmaceuticals and cosmetics. LA can be produced through carbohydrate fermentation using various microorganisms, including lactic acid bacteria (LAB). However, the high production cost of commercial fermentation media for lactic acid raises concerns among researchers. Consequently, there is a demand for research to develop new, more affordable, and sustainable fermentation media. Utilizing underutilized agro-industrial wastes from Malaysia, particularly in the coconut, oil palm, rice, and sugarcane processing industries, offers several advantages. These include biomass reuse, cost-effective production of valuable chemicals, and agricultural waste reduction. This review discusses the potential of underutilized Malaysian agro-industrial waste from the coconut, oil palm, rice and sugarcane processing industries as sustainable carbon sources for LA production. The topics covered encompass the chemical and nutritional composition of the wastes, their potential for lactic acid fermentation with specific microorganisms, factors influencing lactic acid production, and potential applications. Additionally, this review also highlights the challenges and opportunities associated with reutilizing agricultural waste for lactic acid production.

Keywords: agro-industrial; waste conversion; lignocellulose waste; lactic-acid fermentation; lactic acid bacteria

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1. Introduction

1.1. Underutilized Malaysian Agro-Industrial Waste

Agro-industrial waste represents a significant environmental challenge in Asia. The region produces approximately 1.3 billion tons of agro-industrial waste annually, while only a small fraction is recycled or composted. Malaysia, a prominent agricultural producer in Southeast Asia, generates substantial waste from agricultural activities [1,2]. Coconut husk, empty fruit bunches (EFB), rice husks and bagasse are among the most common agricultural wastes in Malaysia, as shown in Figure 1 [3–6]. This waste can pollute waterways, contaminate soil, and release harmful gases into the atmosphere. It can also pose a health risk to humans and animals.

However, these wastes hold significant potential for diverse applications, such as biofuels, animal feed, fertilizer, charcoal, activated carbon, construction materials, and textiles. Coconut waste makes up 6.7% of all agricultural waste generated in Malaysia, amounting to 80,000 tons per year [7]. Meanwhile, about 75.61 million tons of solid biomass waste are generated annually in the palm oil industry in Malaysia. This is equivalent to about 1.25 tons of waste per hectare of oil palm plantation. The main components of palm oil biomass waste are EFB, fronds, and trunks [8]. In addition to that, rice husk, the outer layer of rice grains, is abundantly available in Malaysia as a by-product of the rice milling industry. The annual rice husk waste generation in Malaysia is estimated to be around 770,000 tons. This is equivalent to about 200 kg of rice husk per ton of rice produced. The Malaysian government aims to decrease rice husk waste by 50% by 2025 through its promotion as a renewable resource [9,10].

In addition to these common agricultural wastes, Malaysia also generates a sizable amount of sugarcane waste. These include sugarcane leaves, sugarcane bagasse, and sugarcane trash. If these agricultural wastes are not properly disposed of, they could harm the ecosystem. They can attract pests and rodents, and they have the potential to emit dangerous toxins into the air and water.

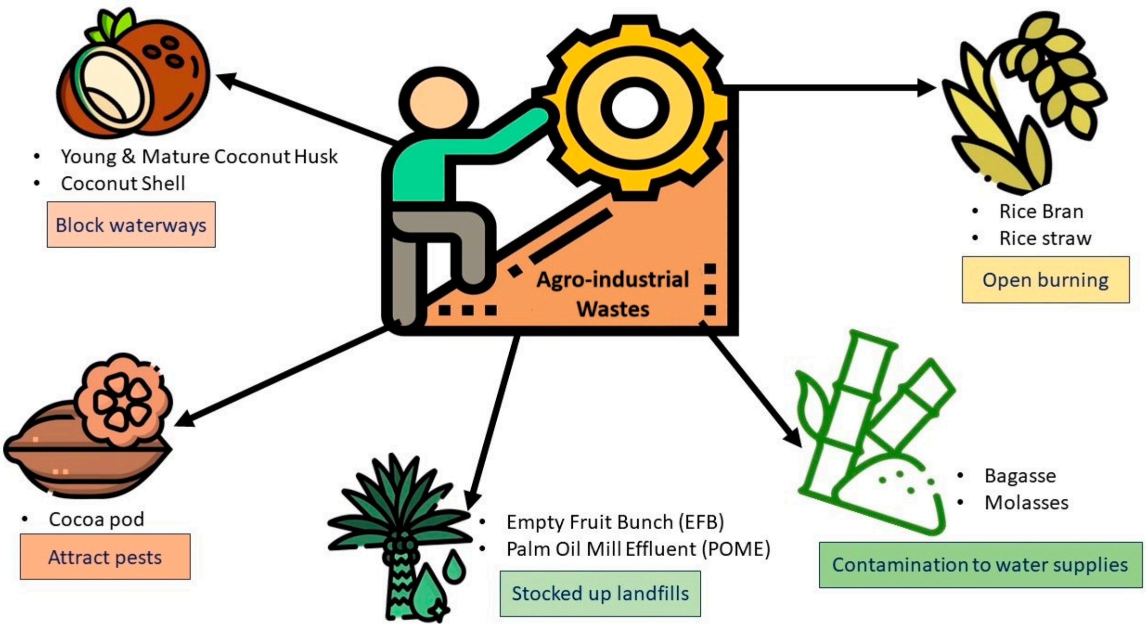

Figure 1. Malaysian agro-industrial wastes and its environmental problems.

However, these agricultural wastes could also be significant resources in the future. Through proper research and development, they can be repurposed to create a variety of products that offer societal benefits. There is rising interest in using agricultural waste in Malaysia, and government agencies offer financial rewards to businesses that find innovative uses for agricultural waste [11]. Many research institutions in Malaysia are actively involved in developing inventive approaches to utilizing agricultural waste. With sustained research and development, it is feasible to utilize Malaysia's agricultural waste and build a more sustainable future ecosystem.

1.2. Production of Lactic Acid from Agro-Industrial Waste

Lactic acid ($C_3H_6O_3$, molecular weight: 90.08 g/mol) is an organic acid that has been used for centuries in the food industry, mainly as a preservative and flavoring agent. Food manufacturers add lactic acid to food as a bio-preservative as it has antimicrobial properties that can inhibit foodborne pathogens, including bacteria, yeast, fungi, and mycotoxins produced by fungi, thus extending the shelf-life of food [12]. Furthermore, lactic acid can also be used as an acidulant and coagulant to improve the taste, texture and aroma of food products. Lactic acid is produced naturally by LAB, which are found in many fermented foods such as yogurt, cheese, and sauerkraut. Lactic acid has received Generally Recognized As Safe (GRAS) status from the FDA [13], which widens its application to not only the food industry, but also pharmaceuticals, bioplastics and biomedical industries [14,15]. In general, lactic acid exists in two isomeric forms, L- and D-lactic acid, which differ in their configuration. The two configurations of lactic acid make it versatile for a variety of transformations and chemical productions. Moreover, it can also exist as a racemic mixture of L- and D-lactic acid, depending on the method of synthesis or production.

Lactic acid can be produced through chemical synthesis or microbial fermentation. Currently, microbial fermentation is the main industrial process for producing lactic acid, accounting for around 90% of global production [16]. It is more environmentally friendly and sustainable for producing lactic acid than chemical synthesis. Fermentation requires lower temperatures and energy resources, and it can produce optically pure D(−) or L(+) lactic acid isomeric compounds or a mixture of DL lactic acid, depending on the strain of microorganism used [17]. For example, LAB *L. coryniformis* subp. *Torquens* produced D-lactic acid [14,15] while *L. Palantarum* produced a mixture of DL-lactic acid. Various fungal species of the *Rhizopus* genus, such as *Rhizopus oryzae*, are able to produce optically pure L(+)-lactic acid. Currently, LAB are known as the main safe industrial-scale lactic acid producers for food application. However, other factors such as temperature of fermentation, agitation speed, substrate concentrations and the presence of inhibitors in fermentation media are crucial in ensuring optimal production of lactic acid via fermentation techniques [15].

Production of lactic acid via fermentation offers the additional advantage of reutilizing agro-industrial waste as a substrate. Apart from reducing environmental pollution, this material is abundantly available at a low cost and does not require much processing, reducing the cost of the final products. In general, the production of lactic acid through the fermentation of agro-industrial waste can be divided into four processing stages, starting with the pretreatment of biomass, followed by saccharification to release fermentable sugars, fermentation by specific or targeted microorganisms depending on the targeted product, and product separation and purification (Figure 2). Various pretreatment strategies have been studied previously, including physical (grinding and extrusion), chemical (alkali, acid, and organic solvent treatment) [18,19], physico-chemical (autohydrolysis, hydrothermolysis, and oxidation), electrical (electric field pulsed and pyrolysis), and biological (fungi and bacteria) [20]. However, the effectiveness of the strategies will depend on the type and composition of agricultural waste used as substrate. For the saccharification process, techniques such as enzymatic, acidic or alkaline hydrolysis were commonly used to release the fermentable sugars from polysaccharides. Enzymatic hydrolysis offers better advantages than other methods, as it is more effective, specific and produces no inhibitors [15,19]. The next stage is the fermentation of the hydrolysate by selected microorganisms to produce lactic acid. This process will normally take between 12 and 48 h at 20 to 35 °C before entering the death phase of the microorganism. At this stage, lactic acid will be produced as the primary metabolite, in parallel with the microbial growth, until fermentable sugar is depleted, or the pH is reduced to <3.5. The produced lactic acid will then be separated and recovered from the fermentation medium in the downstream processing. Unused proteins, sugars and other compounds will be removed to purify the lactic acid. Centrifugation, filtration and solvent extraction are normally used to separate microbial cells from lactic acid solution, followed by purification with precipitation, ion exchange, affinity or gel filtration chromatography, electrodialysis and membrane filtration [17].

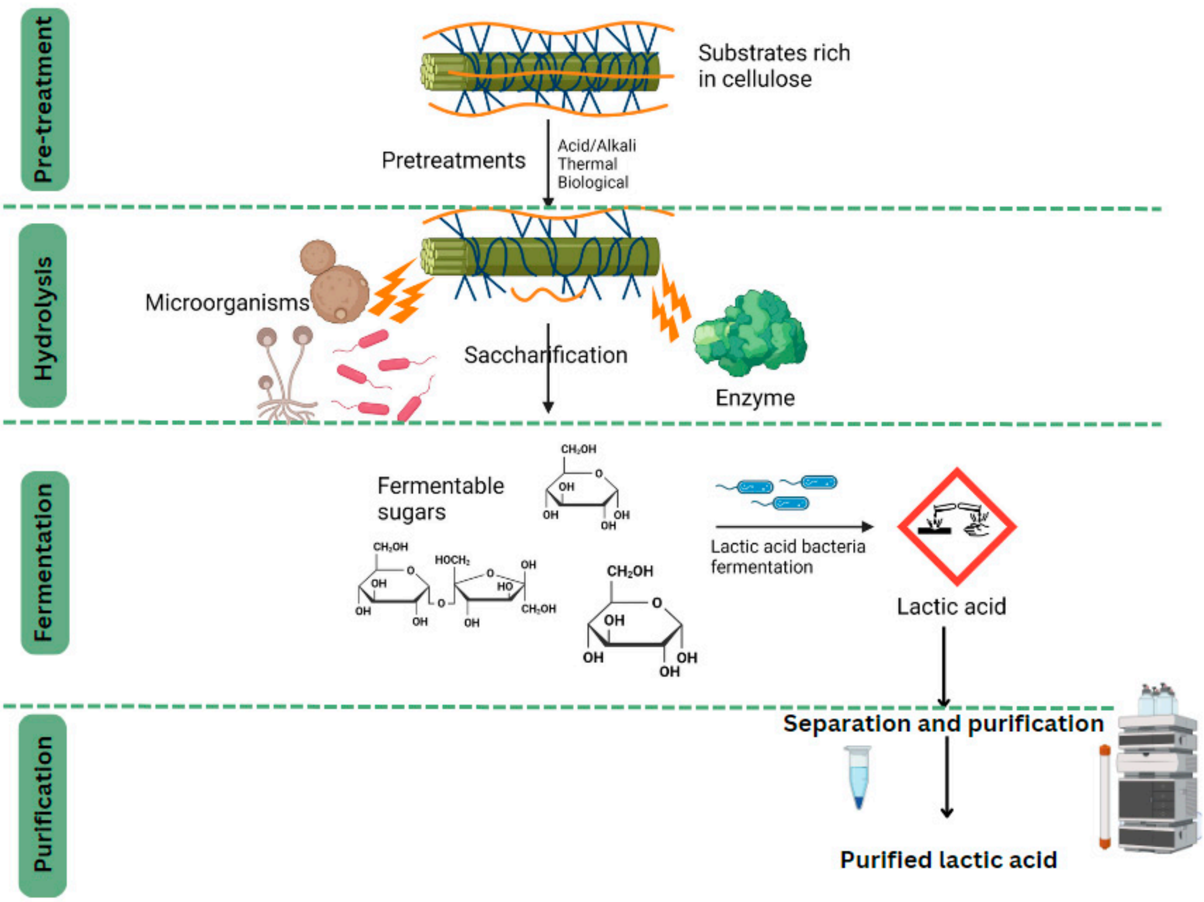

Figure 2. General processing stages involved in lactic acid production from agro-industrial waste.

2. Potential Agro-Industrial Waste as Feedstock for Lactic Acid Production

2.1. Coconut Waste

Coconut (*Cocos nucifera* L.) is one of the most important agricultural crops, especially in the Asian region, including Malaysia, Indonesia, Thailand and the Philippines, which collectively contribute approximately 90% of the world's total coconut production [21]. The Malaysian government allocated RM150 million in the 2020 budget to incentivize crop integration programs, including coconut, for farmers. Coconuts are a versatile crop with many uses. Coconut fruit consists of six parts, starting with the exocarp, the thin outer layer; mesocarp, the fibrous husk; endocarp, the hard shell surrounding the flesh; testa, the very thin layer covering the flesh; meat, or the white flesh of the coconut; and water, the liquid endosperm [22,23]. The water and pulp are the most common parts of the coconut fruit that are consumed in their raw state. However, other products, such as oil, milk, flour, and even soap, can be produced through further processing. These products have a high value in the food, medicine, health, and cosmetics sectors.

However, the development of the coconut plantation sector has generated excessive and significant biomass waste in the country. This waste, which includes coconut husks, shells, empty bunches, and fronds, is normally discarded on embankments and left in an open environment [24]. This will result in waste accumulation and, consequently, soil contamination and pest infestation. The general uses and waste from coconut fruit were further illustrated in Figure 3 [25].

Research into reutilizing or valorizing coconut waste is capturing significant interest from researchers. One promising avenue is to produce lactic acid from coconut waste. The process of producing lactic acid from coconut waste has great potential due to the abundant availability of this agricultural biomass. In the biorefinery process, the cellulose component within coconut waste, particularly from the husk, becomes the focus for lactic acid production. Although coconut shell waste has been extensively investigated for the production of biofuels and bioplastics [26,27] there is a notable absence of studies focusing on lactic acid production from the waste, despite the fact that its cellulose content is reported to be comparable to that of coconut husk waste [28,29]. Moreover, due to the high lignin and hemicellulose content and the robust nature of coconut biomass, more comprehensive studies on technologies and approaches are needed to achieve maximum lactic acid production.

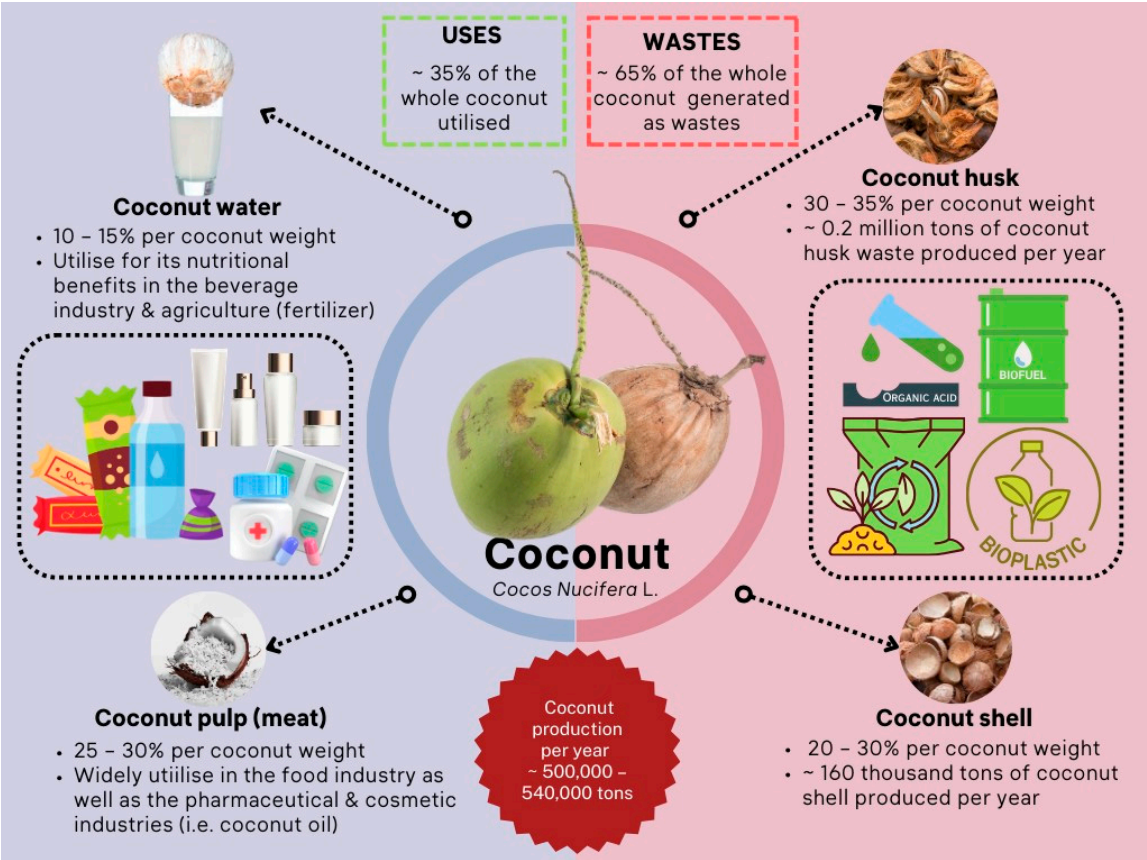

Figure 3. Uses and wastes generated from coconut fruit.

Coconut husk, also referred to as coir, is the fibrous outer layer that covers the coconut fruit, with a thickness of around 5 to 6 cm. In general, for every 1 kg of coconut harvested, 0.6 kg of husk (dry weight) is produced [30]. Coconut husk can be categorized into two groups as the fruits are often harvested at two different maturities depending on the intended application:

1. Mature Husk (from old brown coconuts): These are taken from fully matured coconuts, usually around 12 months old. Mature coconut husk is characterized by its thickness, strength, dryness, and high resistance to abrasion.
2. Young Husk (from green, immature coconuts): These husks are harvested from green and immature coconuts, typically around 6 months old. They appear brownish-white, are moist, flexible, and comparatively weaker. Young coconut husks are finer in texture and can be easily processed using chemical methods.

Malaysia produces approximately around 0.2 million tons of coconut husk annually, based on the yearly coconut production ranging from 500,000 to 540,000 tons [25]. This large amount of agro-waste presents an opportunity to solve the problem of waste disposal by exploiting cheap and unused coconut husk biomass to produce various value-added products. Coconut husk contains a high amount of lignocellulosic polymer that can be further exploited as feedstock, to produce valuable compound, such as lactic acid, mineral components (ash) and other chemicals, such as pyroligneous acid, uronic acid, gas, charcoal, tar and tannins [18,31]. Lignocellulosic biomass can be further hydrolyzed into cellulose, hemicellulose and lignin (Table 1). These components can then be converted into monosaccharides sugar, such as glucose, xylose, and arabinose, which are important substrates in biochemical processes through fermentation.

Table 1. Chemical composition of lignocellulose material from young and mature coconut husk.

Type	Ash (%)	Cellulose (%)	Lignin (%)	Hemicellulose (%)	References
Young coconut husk	2.40	33.32	32.40	14.60	Din et al. [32]
	1.25	29.96	35.46	33.33	Lomelí-Ramírez et al. [24]
	2.56	24.70	40.10	12.26	Cabral et al. [33]
	n.a.	39.31	29.79	16.15	Vaithanomsat et al. [34]
	n.a.	45.93	43.14	n.a.	Brígida et al. [35]
	2.6	35.1	33.6	2.3	van Dam et al. [36]
	n.a.	23–43	35–45	3–12	Carrijo et al. [37]
Mature coconut husk	1.53	23.25	38.80	14.95	Din et al. [32]
	1.6	38.4	31.8	24.5	Sengupta and Basu [38]
	0.61	29.23–36.51	23.81–33.51	15–28	Reddy and Yang [39]
	n.a.	37.11	44.06	n.a.	Khan and Alam [40]
	n.a.	41.55	45.95	31.10	Brígida et al. [35]
	1.34	31.83	45.47	2.33	Salazar et al. [41]
	n.a.	32.1	68.9	16.8	Asasutjarit et al. [42]
	2.4	44.2	32.8	6.4	Khalil et al. [43]
	n.a.	20.5	33.20	31.1	Ramakrishna and Sundararajan [44]

n.a.—not available.

To date, only a few studies have investigated the production of lactic acid from coconut husk. Nor et al. [18] compared the effects of enzymatic hydrolysis and acid hydrolysis on the release of monosaccharide sugars from coconut husk. The author reported the highest monomeric sugar conversion from coconut husk when enzymatic hydrolysis was employed compared to acid hydrolysis. In addition, Din et al. [32] and Din et al. [15] have successfully produced D-lactic acid through a combination of alkaline pretreatment, enzymatic hydrolysis by Accellerase 1500, and fermentation by *Lactobacillus coryniformis* subsp. *Torquens* utilizing mature and young coconut husk. Around 14.93 and 19.88 g/L of D-lactic acid were produced. Besides, another study by Mudaliyar and Kulkarni [45] reported higher estimated lactic acid production from coconut husk with 34 g/L from the strain *Rhizopus oryzae* NCIM 1299. Apart from these, no research on lactic acid production from coconut waste has been reported. For the recovery of lactic acid from fermentation medium, Din et al. [15] have developed innovative separation of D-lactic acid through in situ separation by incorporating ion exchange resin (Amberlite IRA-67) together during the fermentation process, which shows 90% recovery efficiency.

2.2. Oil Palm Waste

Malaysia is acknowledged as a major global producer of palm oil, and as a result, it yields a significant amount of biomass from its oil palm processing. This biomass comprises elements like EFB, oil palm fronds (OPF), oil palm trunks (OPT), palm kernel cakes (PKC), and palm oil mill effluent (POME), as outlined by Boonsawang and Youravong [46]. Study by Bejarano et al. [47] reported that merely 23% of waste and by-products from agro-industry are recycled back into the production process, leaving the bulk of these resources untapped. A breakdown of the weight percentage of these oil palm elements is shown in Figure 4 [48].

2.2.1. Empty Fruit Bunch (EFB)

The processing of fresh fruit bunches (FFB) yields a byproduct referred to as empty fruit bunches (EFB), amounting to approximately 220 to 250 kg per metric ton of FFB processed. EFB's composition, primarily consisting of fermentable sugars derived from cellulose and hemicellulose, cellulose constituting around 35 to 50%, hemicellulose comprising 20 to 30%, and lignin making up 15 to 25% is coupled with minimal residual oil content. The moisture content in EFB varies between 10 and 15% [49].

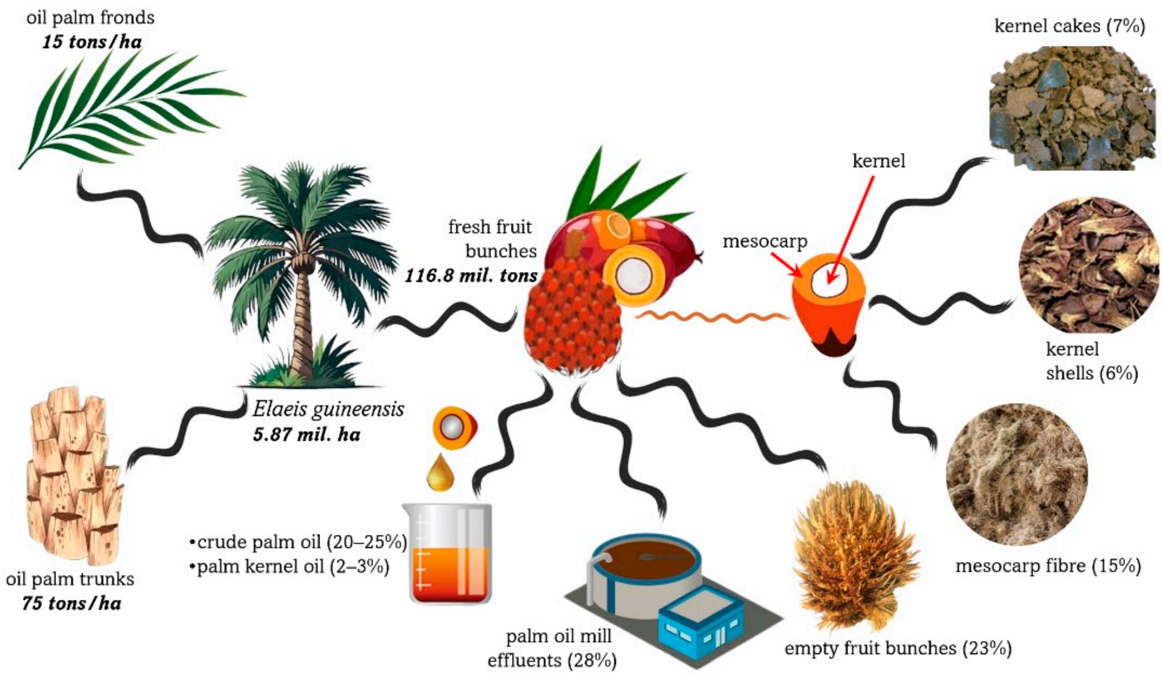

Figure 4. Schematic diagram of the weight percentage of the oil palm components.

In the context of lactic acid production, *Bacillus coagulans* JI12 has demonstrated its effectiveness. It has the unique capability of concurrently converting glucose and xylose into L-lactic acid with a high optical purity of over 99.5%, as revealed by Ye et al. [50]. A similar study reported quick consumption of glucose and L-arabinose within 13 h, whereas xylose was utilized within a span of 24 h. Furthermore, this strain also tolerates high concentrations of furfural (4 g/L) and acetate (20 g/L), efficiently metabolizing furfural into 2-furoic acid. As the fermentation progresses and the furfural concentration decreases, lactic acid production significantly accelerates, achieving an outstanding yield of 80.6 g/L, productivity of 3.4 g/L/h, and a conversion rate of 0.49 g lactic acid per g EFB [50].

In a separate study by Juturu and Wu [49], EFB's potential as a carbon source was explored further. *Bacillus coagulans* JI12 was used to ferment hemicellulose hydrolysate derived from EFB's acid hydrolysis. This process was conducted under unsterilized conditions at 50 °C and pH 6.0. The resulting fed-batch fermentation yielded 105.4 g/L of L-lactic acid at a productivity rate of 9.3 g/L/h. On the other hand, simultaneous saccharification and fermentation (SSF) using the enzyme Cellic CTec2 led to the co-fermentation of hemicellulose hydrolysate and cellulose-lignin complex. Using yeast extract as the nitrogen source, SSF resulted in an L-lactic acid yield of 114.0 g/L with a productivity rate of 5.7 g/L/h. When yeast extract was replaced with dry Bakers' yeast, production elevated to 120.0 g/L of L-lactic acid with a productivity rate of 4.3 g/L/h. These findings underscore the potential of EFB as an economically viable carbon source and Bakers' yeast as a beneficial nitrogen source for lactic acid production.

2.2.2. Oil Palm Trunks (OPT)

The abundance of agricultural waste, like oil palm trunks (OPT), provides an untapped potential for lactic acid production. A study by Erliana et al. [51] explored this possibility by introducing various microorganisms, such as *Lactobacillus acidophilus*, *Lactobacillus casei*, *Lactobacillus brevis*, and *Lactobacillus rhamnosus*, in both single and combined cultures under temperature- and pH-controlled fermentation conditions. The study found that OPT comprises roughly 43.88% cellulose, 7.24% hemicellulose, and 33.24% lignin. Notably, lignin impeded the generation of reducing sugars, which demanded its removal through a pretreatment process. The researchers thus applied acid-organosolv pretreatment using H_2SO_4 at 120 °C for 40 min and organosolv pretreatment with 30% ethanol at 107 °C for 33 min, which led to a significant surge in cellulose content of 56.3% and a decrease in lignin content of 27.1% [51]. Subsequent enzymatic hydrolysis employed commercial cellulase enzymes from *Aspergillus niger* (AN) and *Trichoderma reesei* (TR). It was observed that an AN:TR ratio of 1:2 yielded the highest concentration of reducing sugars. Lactic acid fermentation was conducted at a controlled 37 °C and pH 6 for 48 h. The best lactic acid production was attained using a mixed culture of *Lactobacillus rhamnosus* and *Lactobacillus brevis*, resulting in 33.29 g/L of lactic acid. This mixed culture demonstrated superior results compared to individual cultures of *Lactobacillus rhamnosus* (15.49 g/L) and *Lactobacillus brevis* (15.44 g/L), indicating the enhanced utilization of substrates by microorganisms.

Eom et al. [52] also presented a straightforward and cost-effective method for producing L-lactic acid from OPT. The process entailed hydrothermal treatment, enzymatic hydrolysis, and fermentation of pretreated whole slurry (PWS) of OPT. The process obtained substantial glucose yields of 81.4% and 43.6% from PWS and washed pretreated solid (WPS), respectively. Furthermore, the fermentation of hydrolysates from PWS and WPS, employing *Lacticaseibacillus paracasei* in 2.5 L batch reactors, resulted in lactic acid yields of 89.5% and 45.8% of the theoretical yield, respectively. It is noteworthy that when whole slurry was employed, 47.9 g of lactic acid was produced from 100 g of dried OPT, signifying an efficient conversion rate of 89.5% of glucose into lactic acid [52].

Kunasundari et al. [53] took another approach by focusing on the production of lactic acid using the sap extracted from OPT. Thermophilic *Bacillus coagulans* strain 191 was used, which demonstrated versatility towards various sugars, including the sap's sucrose. The conversion of sap sugars to lactic acid resulted in a moderate yield of 53% and a productivity of 1.56 g/L h^{-1}. To improve fermentability, alkaline precipitation pretreatment of the OPT sap was employed, leading to a significant increase in lactic acid yield (92%) and productivity (2.64 g/L h^{-1}) through reduction of inhibitory phenolic and mineral compounds. Furthermore, Kosugi et al. [54] found that OPT sap obtained from the inner part of the trunk, accounting for more than 80% of its weight, exhibited a high concentration of glucose and was rich in amino acids, organic acids, minerals, and vitamins. Fermentation using *Lactobacillus lactis* ATCC19435 showed that the sap could be readily converted into lactic acid without the need for additional nutrients. The lactic acid fermentation exhibited high efficiency, with a lactic acid yield of 89.9% [53].

Similarly, Saelee [55] examined the use of *Lactobacillus rhamnosus* ATCC 10863 and different fermentation modes to boost lactic acid yield and productivity using undiluted OPT sap. The modified constant feed mode surpassed the repeated open batch fermentation, resulting in higher lactic acid yield (1.04 g/g), productivity (6.40 g/L/h), and a shorter fermentation time (11 h). This study again underscored the potential of OPT as an efficient feedstock for lactic acid production.

2.2.3. Palm Kernel Cakes (PKC)

Palm kernel cakes (PKC) hold a distinct advantage over other oil palm biomass types due to their low lignin and cellulose content, which facilitates easy hydrolysis. These cakes primarily consist of linear mannan polymers made up of β-D-mannopyranose linked by (1→4) bonds, along with α-D-galactopyranose side groups attached by (1→6) bonds. They contain around 25–40% galactomannan, 10–20% glucan, and 45–55% fermentable hexose sugars, with the remaining percentage comprising proteins, fibers, and moisture. Additionally, PKC is rich in crucial macro- and micro-nutrients such as protein, potassium, calcium, sodium, iron, manganese, and phosphorus, making it a cost-efficient base medium for fermentation [56]. The low lignin and cellulose levels in PKC necessitate only mild pretreatment, leading to minimal formation of inhibitory by-products and enabling the production of high-purity lactic acid. However, there are some challenges related to non-sugar components and inhibitory substances in PKC that need to be addressed for efficient fermentation [56].

In research conducted by Rahim et al. [57], they explored the production of lactic acid from PKC using *Actinobacillus succinogenes* 130 Z. The study aimed to understand the effects of different concentrations of oxalic acid and different residence times on sugar recovery. The optimal hydrolysis conditions were determined to be a four-hour duration and a 3% (w/v) oxalic acid concentration, resulting in a maximum mannose concentration of 25.1 g/L. The enzymatic saccharification that followed yielded 9.14 g/L of glucose. A dual-phase cultivation process supplemented with 30 g/L of magnesium carbonate led to the highest recorded lactic acid titer of 19.4 g/L using *Actinobacillus succinogenes* 130 Z. Further improvements in lactic acid production were achieved by utilizing immobilized cell fermentation with differently sized coconut shell-activated carbon. In repeated batch cultivation, immobilized cells generated 31.64 g/L of lactic acid, showcasing enhanced performance.

2.2.4. Palm Oil Mill Effluent (POME)

Palm oil mill effluent (POME) is typically composed of around 1 to 4% total solids, 80 to 95% volatile solids, 0.1 to 0.6% lipids such as fats and oils, 0.2 to 1.5% carbohydrates, and around 0.1 to 0.8% proteins. The effluent also contains varying concentrations of organic acids. Its complex composition, especially the high lipid content, can present obstacles during the fermentation process. A past study focused on producing L-lactic acid from POME using a locally isolated *Enterococcus gallinarum* EB1 strain [58]. The strain was capable of producing 18.0 g/L of L-lactic acid from 20.0 g/L of glucose. As for the recovery of lactic acid, the most efficient method entailed the utilization of H_2SO_4 prior to evaporation at 90 °C under a vacuum pressure of 3 mmHg. The incorporation of H_2SO_4 facilitated the release of lactic acid from lactate salts that formed during the fermentation process, as NaOH was employed to maintain the pH. Through the evaporation method, a recovery yield of 86.76% lactic acid was achieved from the fermentation broth, which marked the highest yield recorded using evaporation methods [58].

Given the plentiful carbohydrates and other advantageous nutrients they contain, these biomass materials could be a prospective carbon source for lactic acid production (Table 2).

Table 2. Comparison of lactic acid production from oil palm carbon sources using different biocatalysts.

Carbon Sources	Composition	Promising Biocatalyst	Titer (g/L)	Yield (g/g)	Productivity (g/L h^{-1})	References
Empty fruit bunches	cellulose: 35–50%; hemicellulose: 20–30%; lignin: 15–25%	*Bacillus coagulans* JI12	80.6 120.0	0.49 0.99	3.4 4.3	Ye et al. [50] Juturu and Wu [49]
Oil palm trunks	cellulose: 43.88%; hemicellulose: 7.24%; lignin: 33.24%	*Lactobacillus rhamnosus* and *Lactobacillus brevis*	33.29	0.68	0.69	Erliana et al. [51]
		Lacticaseibacillus paracasei KM2	38–40	0.49	1.36–1.43	Eom et al. [52]
		Bacillus coagulans 191	63.3	0.92	2.64	Kunasundari et al. [53]
		Lactobacillus rhamnosus ATCC 10863	95.94	1.04	6.40	Saelee [55]
Palm kernel cakes	galactomannan: 25–40%; glucan: 10–20%; sugars: 45–55%	*Actinobacillus succinogenes* 130 Z	31.64	0.92	0.88	Rahim et al. [57]
Palm oil mill effluents (origin)	total solids: 1–4%; VSS: 80–95%; lipids: 0.1–0.6%; carbohydrates: 0.2–1.5%; proteins: 0.1–0.8%	*Enterococcus gallinarum* EB1	18.0	1.92	N/A	Chung [58]

2.3. Rice Waste

Given the annual global rice production of approximately 1.3 billion tons, the accumulation of rice waste has emerged as a notable concern, estimated to encompass a range of 260 to 390 million tons per year. This represents a substantial amount considering that 20 to 30% of the total production goes to waste. The large quantity of rice waste poses challenges in terms of food availability, contributing to issues of hunger and malnutrition when edible rice is discarded. Furthermore, rice waste has detrimental environmental effects, such as water pollution and greenhouse gas emissions. In 2017, greenhouse gas emissions resulting from the burning of rice residues accounted for nearly 54.634 megatons of CO_2 equivalents [59]. This highlights the need to address the environmental and economic concerns associated with rice waste.

To tackle these challenges, recent studies have focused on the sustainable utilization of rice by-products within a biorefinery concept. By adopting this approach, the by-products of the rice production process can be effectively utilized, reducing waste, and promoting a more circular economy. Countries like China, India, and Indonesia, which are major rice producers, generate a significant portion of the annual rice waste, accounting for nearly half of the total amount, approximately 200 million tons [59]. The utilization and management of rice waste exhibit variations across different countries and regions. In some areas, rice waste finds its purpose as animal feed, contributes to energy generation, is used for biofuel production, or serves as a raw material for diverse industrial applications. Rice waste encompasses the by-products and residues generated during rice production and processing. It includes rice husk, rice straw, and rice bran (Figure 5).

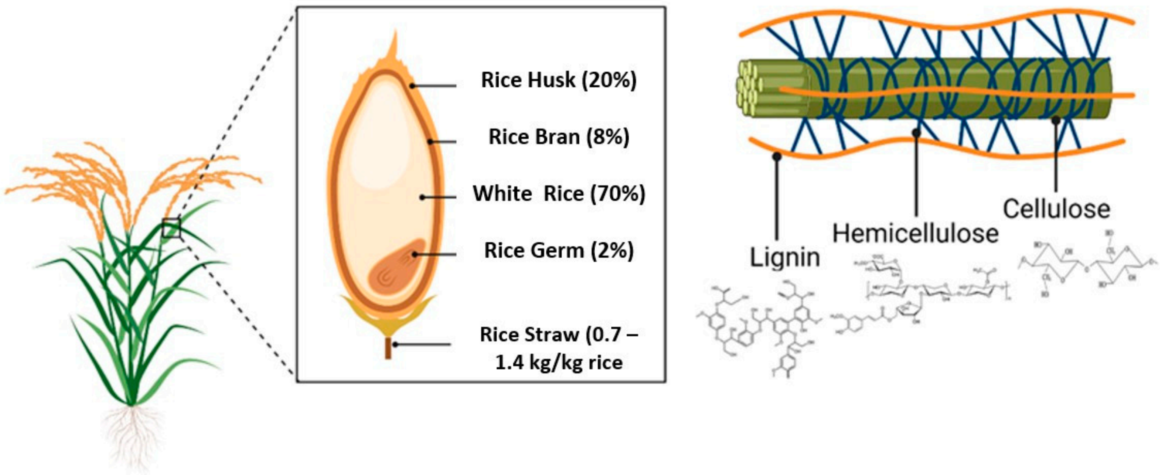

Figure 5. The structure of rice. The husk, bran, and straw are typically discarded as waste.

Ongoing efforts are dedicated to exploring innovative uses for rice waste, including the production of biodegradable materials, dietary fiber, and functional food ingredients. One promising approach involves lactic acid fermentation, wherein rice waste components like rice husk, rice bran, rice straw, and broken rice can be utilized as substrates for lactic acid production. Among these waste components, rice husk and rice straw pose greater challenges for valorization due to their high content of hemicellulose, lignin, silica, and other inhibitory substances [60]. These components impede the hydrolysis process, restricting the conversion of complex polysaccharides into fermentable monosaccharides.

Generally, pretreatment processes of rice wastes are conducted to separate lignin from cellulose and reduce the protective barriers of hemicellulose. The processes facilitate increased accessibility of cellulose to chemical and enzymatic action, enhancing the conversion process. Table 3 provides examples of pre-treatment studies conducted in this context on rice wastes, which aim to release fermentable sugars that can be used as substrates for lactic acid microbial fermentation. It is important to note that numerous similar studies have been conducted, employing a variety of approaches, including physical, thermal, and biological (utilizing microorganisms or enzymes), as well as combinations of these methods, to pre-treat recalcitrant carbohydrates.

Table 3. The examples of pre-treatments to obtain fermentable sugars from rice waste using different strategies.

Pre-Treatment	Waste	Parameters	Outcome	Reference
Grinding (physical)	Bran	Using FW80 disintegrator and passed through an 80-mesh sieve	Physical pre-treatment is usually performed for bran, to increase its functionality in food-related applications	Zhao et al. [61]
Steam explosion (thermal)	Husk and straw	180–230 °C for 10 min	Rice husk is more resistant than its straw—requires high temperature, lower yield, and higher cellulase for saccharification, with less fermentation theoretical yield	Wood et al. [62]
Phanerochete chrysosporium (biological—microbe)	Husk	30 C, 150 rpm for 26 days in a shaking incubator	Fungal pre-treatment produced fermentable sugars and lignin degradation enzymes in a single instead of 2 steps	Potumarthi et al. [63]
Laccases enzyme (biological—enzyme)	Husk and sugarcane bagasse	Crude laccases enzyme from *Trametes villosa*	10-fold increase in fermentable sugars	Matei et al. [64]
Alkaline treatment and acid hydrolysis (chemical)	Husk	5% or NaOH with strong acid (H_2SO_4) and weak acid (HNO_3) in autoclave	Increase in cellulose and its crystallinity, and thermal properties	Hafid et al. [65]
Thermal assisted alkaline (combination)	Husk	Biomass (10% *w*/*w*), particle size (0.25–0.625 mm), NaOH (2% *w*/*w*), and time (40 min)	Highest sugar production, removal of lignin and no cellulosic components, low hemicellulose, increase in cellulose and its crystallinity, porosity and biomass disruption	Shahabazuddin et al. [66]

After undergoing pre-treatments, rice waste is typically subjected to fermentation by lactic acid bacteria (LAB) or other lactic acid-producing microbial strains, such as filamentous fungi or yeast. The fermented broth is then purified to recover lactic acid through processes like filtration, evaporation, and crystallization. Fungi have shown the ability to produce lactic acid with high optical purity, although their cultivation requires precise morphological and fermentation control. Yeast can also be a viable option for lactic acid production by expressing specific genes, such as LDH, JEN1, and ADY2, while knocking out PDC1. However, bacteria are often considered the optimal choice for lactic acid production due to their high lactic acid yield, optical purity, minimal byproduct formation, and lower power consumption [67]. Various LAB strains, including *Lactobacillus delbrueckii*, *Lactobacillus plantarum*, *Lactobacillus rhamnosus*, and other LAB capable of hydrolyzing lignocellulosic materials, have been employed in the production of lactic acid from rice waste [68].

Substantially, lactic acid derived from rice waste holds significant potential for various applications across industries, including food and beverage, biodegradable plastics, personal care, and pharmaceutical products, as well as agriculture and animal feed. Among these applications, the production of biodegradable polymers, particularly polylactic acid (PLA), stands out as a primary use for lactic acid obtained from rice waste. Furthermore, PLA derived from rice waste has shown excellent potential as active packaging due to its antimicrobial, antioxidant, and preservation properties [69]. Recent research indicates that it possesses notable antioxidant activity, primarily attributed to phenolic compounds, and demonstrates favorable thermal and barrier properties. However, it is important to note that its stability may be somewhat reduced [70].

2.3.1. Rice Husk

Lactic acid derived from rice waste has been found to exhibit favorable qualities. Modification of the structure and composition of rice husk through pretreatment processes, enabling its conversion into valuable products. When treated, rice husk, especially through chemical treatments, exhibits superior properties for biocomposite materials [71,72]. Notably, rice husk contains a significant amount of cellulose (up to 40%) that often remains unused and is either discarded as low-value biofertilizer or burned on-site [73]. Through steam explosion pretreatment of rice husk, followed by co-fermentation with *Penicillium echinulatum* S1M29, *Lactobacillus buchneri* NRRL B-30929, and *Saccharomyces cerevisiae* CAT-1, Montipó et al. [74] successfully produced 12.69 g/L of lactic acid and 19.17 g/L of ethanol, showcasing the potential of a greener bioconversion technique for lactic acid production. However, due to the recalcitrant nature of the rice husk waste, production can still be low due to the presence of inhibitors or a lack of fermentable sugars.

In a recent study conducted by Jaichakan et al. [75], a two-stage saccharification process was employed on rice waste using hydrothermal treatment to produce a substrate with prebiotic properties, specifically xylooligosaccharides. The aim was to create an environment conducive to the growth of LAB strains, namely *Lactobacillus sakei* and *Lactobacillus brevis*, which were protected through high-pressure preservation treatments. Rice waste was considered suitable for this purpose due to the presence of arabinoxylan with an appropriate degree of polymerization. A similar finding was observed by da Silva Menezes et al. [76], who used biological pre-treatments on rice husk involving *Aspergillus brasiliensis* BLf and recombinant *Aspergillus nidulans* XynC A773 to produce xylanases and xylooligosaccharides for the cultivation of *Lactobacillus plantarum* BL011 and *Bifidobacterium lactis* B-12.

2.3.2. Rice Straw

Rice straw, like other plant products, is principally composed of cellulose, hemicellulose, and lignin, which are of significance since they may be broken down into sugars. Considering the similarities in structure and composition with other agrowastes, such as wheat straw [77], the LAB used in the pretreatment of wheat straw substrates may also be applied to rice straw to produce lactic acid. Notably, Verma and Subudhi [78] identified a LAB strain isolated from spent dairy water that exhibited high efficiency, utilizing rice straw biomass sugar with up to 96% efficiency. A mutant strain of *Lactobacillus paracasei* lacking the ldhD gene demonstrates high efficiency, producing up to 215 g/L of optically pure lactic acids from rice straw under optimal glucose conditions, which is one of the highest reported yields in the literature [17]. However, when rice straw is used as the substrate, the yield decreases to 66 g/L, although the strain still maintains high productivity rates and yields [79].

To enhance the capabilities of bacteria during the bioconversion into lactic acid, the removal of fermentation inhibitors in rice straw was found to be essential. Rice straw contains polyphenols that can inhibit the growth of LAB, or lactic acid production, by fungi. Polyphenols such as p-coumaric acid (p-CA), ferulic acid (FA), and condensed tannins released during saccharification were shown to prolong the lag phase, thereby reducing the yield of lactic acid typically produced during the exponential phase. Alkali pre-treatment of rice straw, which reduces these compounds, has demonstrated a significant improvement in lactic acid production [80,81]. The polysaccharides present in rice straw can also have a stimulatory effect, and the removal of polyphenols can lead to lactic acid production, but with lower glucose consumption as a side effect [82].

Yao et al. [83] indicated that the addition of a surfactant during simultaneous saccharification and fermentation can enhance enzymatic hydrolysis, resulting in a greater yield of lactic acid. Moreover, the inclusion of specific growth stimulants in the media, such as potassium diformate, sodium diacetate, and calcium propionate, has been shown to improve the microbial flora during fermentation. For example, these stimulants enhance the growth of *Lactobacillus parabrevis* in mixed rice straw, leading to greater lactic acid production [84].

2.4. Bagasse

Sugarcane, which belongs to the perennial grass family, is primarily cultivated in tropical and subtropical regions of the world. According to the Food and Agriculture

Organization of the United Nations [85], sugarcane is the most widely produced crop globally, with approximately 1.87 billion tons harvested in 2020. While sugarcane is primarily grown for sugar and juice production [86–88], the processing of this crop also yields other valuable products such as prebiotics, bagasse, brown sugar, molasses, and jaggery [89,90].

Bagasse is the fibrous residue that remains after the extraction of juice from sugarcane. It primarily consists of cellulose (40 to 50%), hemicellulose (25 to 35%), and lignin (20 to 30%). This agro-waste accounts for up to 30% of the final product and meets the criteria of second-generation feedstocks: abundant, non-edible, and renewable [91]. While bagasse is commonly used for energy generation for the mill, it is a carbohydrate-rich substrate (over 60%) that can be utilized for the production of various value-added chemicals. However, proper pretreatments are necessary to break down the polysaccharides in bagasse and unlock its potential.

In recent research on the life cycle assessment, different scenarios were developed for lactic acid production based on 200 tons/day of sugarcane bagasse and leaves, employing steam explosion pretreatment [92]. The process involved fermentation with *Lactobacillus* spp. or other potential bacteria, such as an *Escherichia coli* mutant, to generate lactic acid. The study revealed that the use of $Mg(OH)_2$ as a lactic acid neutralizer to prevent the accumulation of undissociated lactic acid yielded the most environmentally and cost-friendly lactic acid production. The use of acid-tolerant thermophilic bacteria (*Bacillus coagulans*) ranked second, followed by $Ca(OH)_2$ as a neutralizer in fermentation.

Currently, extensive research is underway regarding the pretreatment and utilization of bagasse for lactic acid production, as recently reviewed by Agrawal and Kumar [91]. Their review provides a comprehensive summary of lactic acid production from sugarcane bagasse, a second-generation feedstock, as depicted in Figure 6. The recalcitrant bagasse is pretreated to obtain fermentable sugars with low inhibitors before proceeding to lactic acid bioconversion using microorganisms. The authors emphasize that microbial fermentation is the dominant method (~90%) for lactic acid production. They highlight the importance of optimizing costs (CAPEX, OPEX), minimizing waste and water usage, which could significantly improve the socio-economic conditions of developing countries reliant on sugarcane-based agricultural products. Furthermore, the review showcases emerging pretreatment approaches such as dry acid pretreatment and biodetoxification (DryPB), single or twin-screw extrusion, biomass densification using pelletization techniques combined with autoclave (DLCA) or recycled ammonia (COBRA), as well as chemical recycling methods.

During the enzymatic saccharification process to produce fermentable sugars, the cost of cellulase application becomes a limiting factor, particularly on high solids loading of bagasse [93]. To overcome this challenge, the use of auxiliary enzymes for non-glucan components and lignin-blocking additives (such as surfactants and non-catalytic proteins) has emerged as an alternative approach to reduce the dependence on cellulase [94]. Achieving high sugar productivity is crucial for reducing the duration of the process and improving enzyme recyclability, directly impacting the overall cost. Notably, alkali pre-treatment in combination with the Cellic CTec3 enzyme has demonstrated some of the highest reported productivities, exceeding 2 g/L. h along with excellent carbohydrate conversion yields (above 80%) [95,96]. The combination of appropriate pre-treatments and enzyme saccharification is essential, as optimal processes can lead to the recovery of more than 75% of the theoretical fermentable sugars (725 g) from sugarcane bagasse [97]. These advancements offer promising strategies for enhancing the efficiency and cost-effectiveness of enzymatic saccharification processes.

As previously mentioned, the microbial route is the primary method for lactic acid production from bagasse. However, this approach poses several challenges, including the selection of an optimal strain with xylose-associated metabolic genes, minimal carbon catabolite repression, and limited byproduct formation, as well as the requirement for achieving optical purity of the product [98]. From a fermentation perspective, end product inhibition and substrate quality, including the presence of inhibitory compounds, are inherent concerns. Therefore, to enhance lactic acid production from sugarcane bagasse, valuable strategies include strain optimization through techniques like mutagenesis as well as improving fermentation conditions by employing multistep fermentations or substrate detoxification methods. These approaches offer potential solutions to overcome the challenges associated with microbial lactic acid production from bagasse [91].

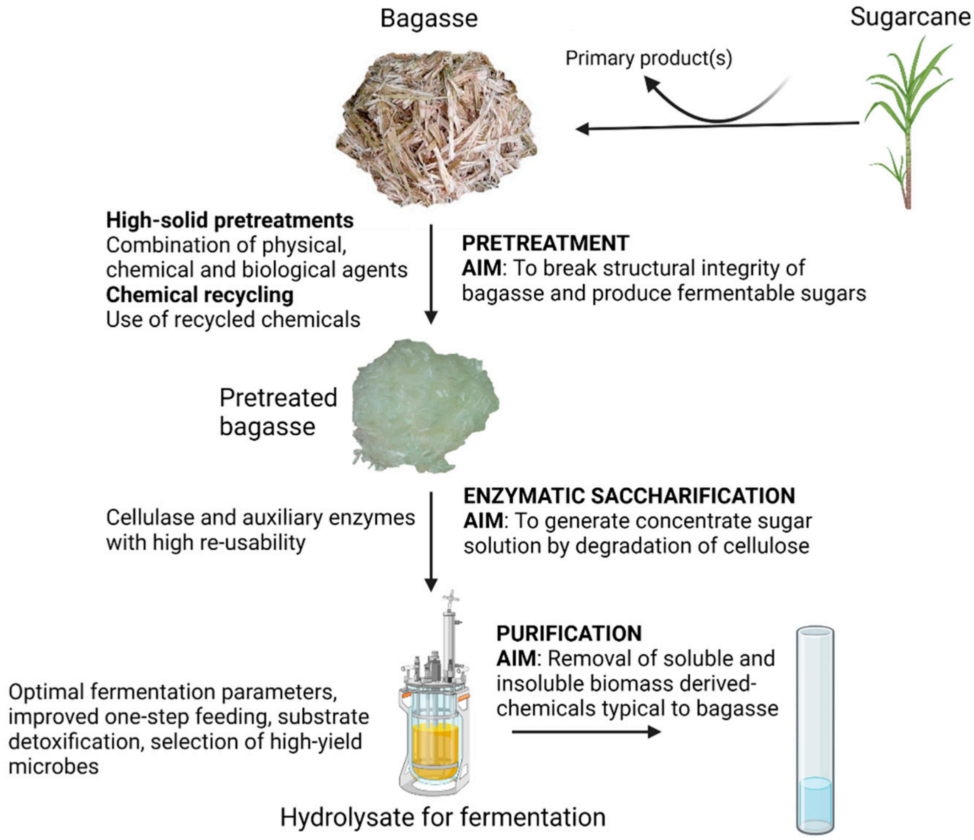

Figure 6. The summary of the bioconversion of sugarcane bagasse into lactic acid. The authors generated the original figure using the information sourced from [91].

Recent investigations have highlighted the superiority of thermotolerant *Bacillus* species over *Lactobacillus* species in strain selection for lactic acid production. In a groundbreaking study by Peng et al. [99], *Bacillus* sp. P38 demonstrated remarkable performance, achieving a lactic acid production of 185 g/L with a yield (g/g) close to the theoretical maximum of 1. Other studies have also shown the potential of *Bacillus* species, particularly *Bacillus coagulans*, to produce lactic acid at concentrations exceeding 70 g/L with yields above 0.7 g/g. *Lactobacillus* species, on the other hand, have demonstrated promising results, typically yielding lactic acid in the range of 60–90 g/L [91]. Another emerging approach involves exploring alternative microorganisms such as yeast, which exhibit stability for gene expression and resistance to inhibitors. By introducing appropriate lactic acid production genes, such as D-lactate dehydrogenase from LAB, yeast has shown promise as an alternative host. However, further research is required to optimize the bioconversion process, as current studies using yeast still demonstrate relatively low productivity (around 20–30 g/L) and yield (around 0.5 g/g) of lactic acid [100,101].

3. Challenges, Limitation and Future Works

Malaysia is a major agricultural producer, and as such, it generates a significant amount of agricultural waste [102,103]. But this waste is frequently underused. To effectively boost the use of underutilized agro-industrial waste, several challenges and limitations, as listed below must be resolved:

- Lack and disconnect of knowledge: Farmers and other stakeholders are often unaware of the potential applications for agro-industrial waste that hold many benefits. Also, researchers are unable to communicate their research findings to the community; for example, the purification strategies can be conducted to increase the yield of targeted products.
- Technical issues: Some technical challenges need to be addressed to use agro-industrial waste in some of its potential applications, such as the production of organic acids, biofuels and bioplastics. For example, most microbes cannot directly metabolize lignocellulose, which requires some strategies to optimize agro-industrial waste utilization [104].
- Infrastructure issues: The infrastructure needed to collect and process agro-industrial waste is either lacking, high-tech or expensive.

Despite these challenges, there is growing interest in using underutilized Malaysian agro-industrial waste due to the potential benefits, including reducing the amount of waste that is sent to landfills or incinerators, which could help to decrease the environmental impact of agriculture. Besides the economic benefits, agro-industrial waste could potentially create new jobs and businesses in the areas of biofuel production, animal feed production, soil amendment, construction materials, textiles, and bioplastics. In addition to that, the prospects for sustainability by reducing the need for imported materials and creating a circular economy should be highlighted. With more research and development, the difficulties in maximizing the use of underutilized Malaysian agro-industrial waste can be overcome. It is possible to utilize this priceless resource and build a more sustainable future for Malaysia with continuous investment in this area. Here are some additional factors to think about in addition to the difficulties and potential advantages previously mentioned:

- The government can play a role in supporting the use of underutilized Malaysian agro-industrial waste by providing financial incentives to companies that develop new ways to use this waste;
- Research institutes can play a role in developing new technologies for the use of underutilized Malaysian agro-industrial waste;
- Farmers and other stakeholders need to be educated about the potential applications of agro-industrial waste;
- The infrastructure for collecting and processing agro-industrial waste needs to be improved.

It is possible to overcome the difficulties and reap the potential rewards of utilizing agro-industrial waste with the help of the government, research organizations, farmers, and other stakeholders.

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