DTU Library

Valorization of municipal organic waste into purified lactic acid

Thygesen, Anders; Tsapekos, Panagiotis; Alvarado-Morales, Merlin; Angelidaki, Irini

Published in:
Bioresource Technology

Link to article, DOI:
10.1016/j.biortech.2021.125933

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Bioresource Technology 342 (2021) 125933

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Valorization of municipal organic waste into purified lactic acid

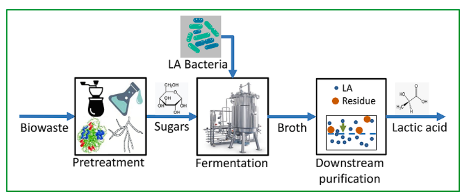
Anders Thygesen, Panagiotis Tsapekos, Merlin Alvarado-Morales, Irini Angelidaki *

Bioconversion Group, Department of Chemical and Biochemical Engineering, Technical University of Denmark, Søltofts Plads 228A, DK-2800 Kgs. Lyngby, Denmark

HIGHLIGHTS

- Municipal organic waste conversion to lactic acid, challenges and opportunities.
- Enzymatic hydrolysis of lignocellulose and food waste into fermentable sugars.
- Fermentation into D and L lactic acid isomers dependent on bacterial strain.
- Continues fermentation resulted in highest productivity due to high cell density.
- Downstream purification of lactic acid using membrane and distillation approaches.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Lactic acid
Municipal organic waste
Enzymatic hydrolysis
Pre-treatment
Fermentation

ABSTRACT

Municipal organic waste (biowaste) consists of food derived starch, protein and sugars, and lignocellulose derived cellulose, hemicellulose, lignin and pectin. Proper management enables nutrient recycling and sustainable production of platform chemicals such as lactic acid (LA). This review gathers the most important information regarding use of biowaste for LA fermentation covering pre-treatment, enzymatic hydrolysis, fermentation and downstream processing to achieve high purity LA. The optimal approach was found to treat the two biowaste fractions separately due to different pre-treatment and enzyme needs for achieving enzymatic hydrolysis and to do continues fermentation to achieve high cell density and high LA productivity up to 12 g/L/h for production of both L and D isomers. The specific productivity was 0.4 to 0.5 h^{-1} but with recalcitrant biomass, the enzymatic hydrolysis was rate limiting. Novel purification approaches included reactive distillation and emulsion liquid membrane separation yielding purities sufficient for polylactic acid production.

1. Introduction

Huge amounts of municipal organic waste (biowaste) are generated in cities such as discarded food and fibrous lignocellulose such as vegetable leaves and wastepaper. It is estimated that over 2 billion tonnes of biowaste is generated per year and with a large part of it not managed in an environmentally safe manner thereby creating a huge environmental challenge (Kaza et al., 2018). Biowaste has either been disposed in untreated form or at best incinerated only utilizing the heating value. In this way, the energy content of biowaste is utilized, although the nutrients are lost. The European Union has banned that biowaste is disposed in landfills and is targeting that 65% of biowaste will be reused and recycled by the year 2023 (EC. Council, 2018; EC. Council, 1999). To recycle biowaste, separation and collection are implemented in EU and will be compulsory by the year 2023. Besides Europe, many countries worldwide, attempt to implement new technologies for the utilization of biowastes.

In recent years, awareness of the challenges our planet is facing has

* Corresponding author.
E-mail addresses: athy@kt.dtu.dk (A. Thygesen), ptsa@kt.dtu.dk (P. Tsapekos), meal@kt.dtu.dk (M. Alvarado-Morales), iria@kt.dtu.dk (I. Angelidaki).

https://doi.org/10.1016/j.biortech.2021.125933
Received 29 July 2021; Received in revised form 7 September 2021; Accepted 8 September 2021
Available online 15 September 2021

changed the perception of how we treat waste globally. The awareness has led to new approaches for holistic production, consumption of products and has resulted in consideration of biowastes to be perceived as bioresources. This approach has also been connected to the economy, driven by the wish to combine sustainability with welfare and life quality offered by the high technological development achieved in the last 100 years. This has been formulated in the bioeconomy approach, which relies on renewable natural resources to produce food, bio-products, biochemicals, biofuels and energy. This approach will decouple our lifestyle from fossil fuel consumption, while at the same time prevent biodiversity loss and minimize the negative impacts on the environment. One element is to use waste and residual bioresources and thereby create a circularity or cascade-based system, where everything is reused with the least energy expenditure and waste production since outputs of one process are used in another process in the desired bio-refinery concept.

Consideration of environmental sustainability and reduced utilization of raw materials are the key objectives of improved waste management. New biomass is also not an endless resource and cannot entirely substitute fossil fuel resources. With the current development, heat and electricity can efficiently be generated by other renewable sources such as solar and wind energy. Therefore, we need to focus on using biomass resources for production of valuable products. There are many suggestions of bioproducts, which can be based on biowaste as substrate. Thereby it has been proposed that biowaste can be used for the production of single-cell proteins (Khoshnevisan et al., 2019), succinic acid (Olajuyin et al., 2019), volatile fatty acids (Yin et al., 2016), polyhydroxyalkanoates (Nielsen et al., 2017) and many others. One very attractive use of biowaste is the production of lactic acid (LA), which is supported by the high content of LA in fermented biowaste (Ahmad et al., 2020; Zhang et al., 2021a). It has been reported that the natural flora in biowaste has a large content of lactic acid bacteria (LAB). Therefore, it can be assumed that unsterilized biowaste can naturally ferment the contained sugars into LA (Probst et al., 2013) as outlined in Fig. 1.

LA (2-hydroxypropionic acid) is the simplest hydroxycarboxylic acid which occurs in the optically active levoratory (L-LA) and dextrorotatory form (D-LA). Due to the reactive hydroxyl group (–OH) and carboxyl group (–COOH), LA can undergo several chemical conversion reactions, which makes it a versatile platform chemical.

The most recent reviews about LA production and achievable products are outlined in Table 1. The topic of lactic acid research has been reviewed on substrate sources covering biowaste (Ahmad et al., 2020; Ajala et al., 2020; Alexandri et al., 2019; López-Gómez et al., 2020b; Nduko and Taguchi, 2021). Lactic acid production has been covered using catalysts (Razali and Abdullah, 2017) and fermentation with LAB (Martinez et al., 2013; Peng et al., 2020; Rawoof et al., 2021). Lactic acid purification by downstream processing have been studied (Ghaffar et al., 2014; Jantasee et al., 2017; Komesu et al., 2017a; Kumar et al., 2019; Li et al., 2021a) including prospects for polymer production (Hamad et al., 2018; Kowalewska and Nowacka, 2020; Michalski et al., 2019; Riaz et al., 2018; Yildirim et al., 2018). These reviews concentrate mainly on few steps in the value chain creating a need for a holistic review of these steps from carbon source until downstream processing. It is also important to consider the achieved purity and isomeric L and D forms for further utilization. Biowaste also consists of animal waste, which

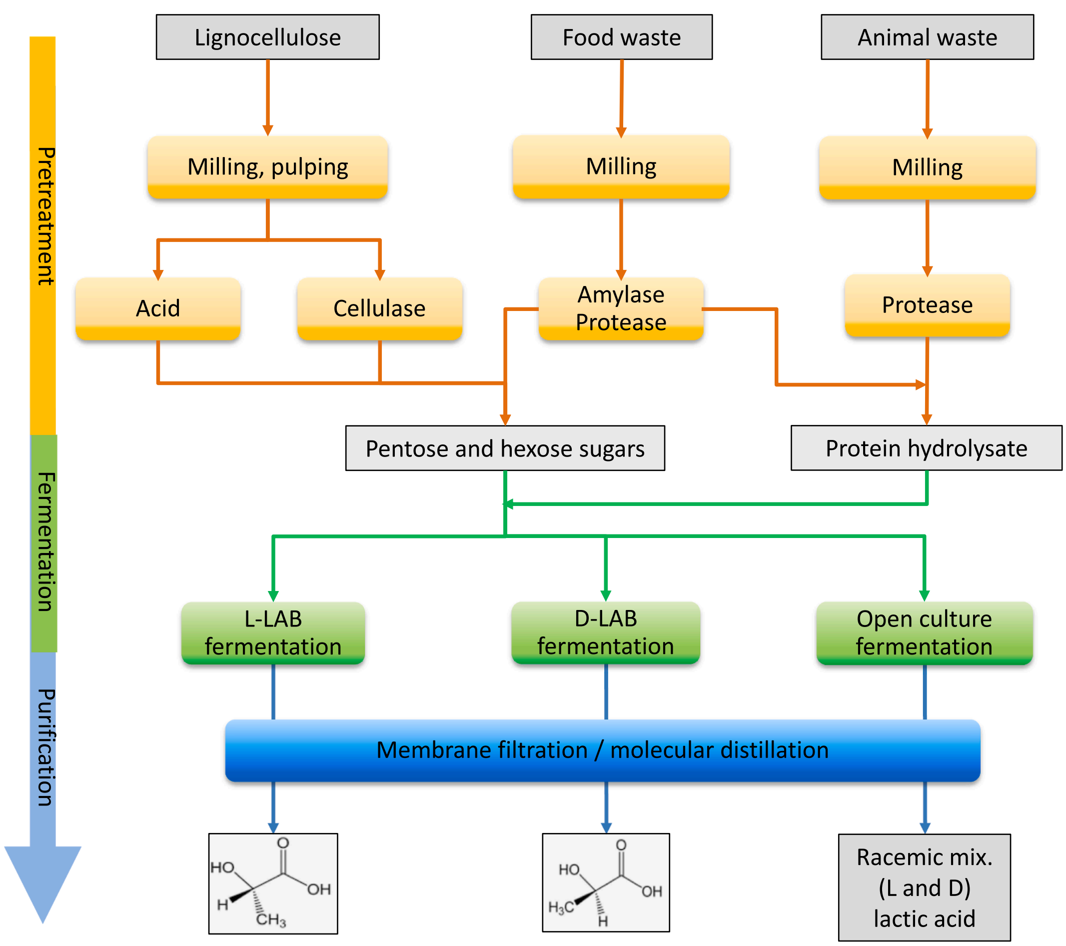


Fig. 1. Overview of the path from biowaste to lactic acid covering pretreatment, fermentation and downstream processing. The enzymatic hydrolysis approaches are shown for lignocellulose, edible biowaste and slaughterhouse waste fractions.

Table 1
Reviews on domestic biowaste for lactic acid fermentation and downstream processing aiming for PLA production published during the last five years.

Carbon waste source			LA production			Downstream processing		Polymerisation			References
Lignocellulose (hydrolysates)	Food	Carbon source	Chemical	Fermentation	Bacteria	Membrane	Separation	Lactide	Synthesis	Products	
		√		√	√						(Bosma et al., 2017)
											(Jantasee et al., 2017)
			√	√	√		√				(Komesu et al., 2017a)
						√	√				(Komesu et al., 2017b)
√		√	√	√	√			√	√	√	(Riaz et al., 2018)
								√	√	√	(Hamad et al., 2018)
								√	√	√	(Yildirim et al., 2018)
√				√ **(D-LA)**	√		√				(Alexandri et al., 2019)
						√	√				(Kumar et al., 2019)
√		√		√ **(continu)**	√						(López-Gómez et al., 2019b)
								√	√**(star shape)**	√	(Michalski et al., 2019)
√	√			√	√	√	√				(Ahmad et al., 2020)
√				√	√						(Ajala et al., 2020)
√	√	√ **(enzymes)**		√	√						(López-Gómez et al., 2020b)
√				√	√						(Peng et al., 2020)
						√	√				(Li et al., 2021a)
√	√**(focus)**	√**(enzymes)**		√ **(focus)**	√	√ **(focus)**	√ **(focus)**	√	√ **(D/L)**		**This review**

includes residues from slaughterhouses, such as skin, meat waste, blood, hairs and bone residues rich in protein. Animal waste has been investigated for several purposes such as production of biogas (Angelidaki et al., 2006). However, animal waste has not been investigated for LA fermentation (Toldrá et al., 2012).

This review focuses on biowaste for LA fermentation and downstream processing required for the use as a platform chemical such as for production of PLA. The biowaste is divided into food wastes, lignocellulosic residues and animal wastes, which makes it possible to rethink the production strategy such as pretreatment and enzymatic hydrolysis of the waste fractions targeting at effective fermentation and downstream processing. Thereby it will be possible to stress out specific challenges of biowastes, which is due to the complex nature of organic matter and also the indigenous microbial conversions needed.

2. Biowaste characterization, pretreatment and hydrolysis

Biowaste consists of discarded food which is primarily starch and meat based and a lignocellulosic fraction containing wastepaper, vegetable residues, plant residues and cellulosic pulp. The composition of these residues is shown in Table 2.

Table 2
Food composition and lignocellulose relating to biowaste composition. The edible food waste is modelled as consisting of protein, fat, carbohydrates and dietary fibers. The lignocellulosic part of food waste contains vegetable residues and paper etc.

Food wastes								Reference
	Fraction (%)	Protein (%)	Fat (%)	Carbohydrates (%)	Sugar (%)	Starch (%)	Plant fibers (%)	
Bakery products	*13*	8	17	**42**	27	14	1	(Hanssen et al., 2016)
Bread	*34*	8	12	**49**	15	30	4	(Hanssen et al., 2016)
Fruit (dried)	*20*	1	0	**16**	11	3	2	(Hanssen et al., 2016)
Vegetables	*20*	2	3	**8**	3	3	2	(Hanssen et al., 2016)
Meat, fish	*13*	16	36	**0**	0	0	0	(Hanssen et al., 2016)
Edible waste	***100***	**6**	**12**	**27**	**11**	**14**	**2**	(Hanssen et al., 2016)
General waste		18	19	**56**		30.2		(López-Gómez et al., 2020b)
Univ cafeteria		18	26	**50**	12	29	8	(Carmona-Cabello et al., 2020)
Fine restaurant		15	33	**46**	18	16	12	(Carmona-Cabello et al., 2020)
Italian restaurant		16	26	**44**	12	23	9	(Carmona-Cabello et al., 2020)
Grill restaurant		13	27	**51**	10	28	13	(Carmona-Cabello et al., 2020)
Lignocellulosic waste		Lignin		**Carbohydrates**	Cellulose	Mannan	Xylan	
Hardwood		28		**65**	46	3	16	(Wu et al., 2021)
Softwood		28		**66**	47	13	5.8	(Wu et al., 2021)
Hardwood CTMP		25		**71**	55	1.5	14	(Wu et al., 2021)
Softwood CTMP		27		**64**	52	6.9	5.1	(Wu et al., 2021)

2.1. Biowaste amounts, value and composition

A study by the United Nations Food and Agriculture Organization found that one-third of the global food production is wasted corresponding to 1.3 billion tons with an estimated value of $750 billion (Pradhan et al., 2021). It has been shown that 3.8 tons of CO_2 are produced per ton if the waste is not properly treated. On the other hand, one-ton food waste could generate 847 kWh electricity or 89 GJ of heating potential when biologically treated for biogas production (Thi et al., 2016). In Europe, food waste at the consumer level accounts for 42% of the total food supply equivalent to 126 million tons by 2020.

A study has investigated food waste composition and separated it into the categories of bread, other bakery products, fruit/vegetables and meat (Hanssen et al., 2016). The waste composition is calculated in Table 2 and separated into 6% protein, 12% fat, 27% carbohydrates, 11% monomer sugar, and 2% dietary fibers. The data show that the protein content mainly originates from meat and carbohydrates from bakery products, vegetables and fruit. The food waste amounted to 58% of the biowaste while the rest 42% was lignocellulose and plant residues. The lignocellulosic part of the biowaste contains vegetable residues and pulp fibers from waste paper. These wastes are rich in cellulose, hemicellulose sugars and lignin (Wu et al., 2021).

Studies on food waste comparing different restaurant types have shown varied protein content of 13 to 18%, fat contents of 26 to 33% and total carbohydrate contents of 44 to 51%. The carbohydrate content consisted of 10–18% sugar, 23–29% starch, 4% cellulose and 4–9% hemicellulose. These results agreed on carbohydrate content with an Asian study showing 54% carbohydrates, 2.1% organic nitrogen and 9% oil/grease (Thi et al., 2016). Variations are expected between countries, due to seasonal variations, fractions of lignocellulosic residues in the biowaste and applied sampling methods. The high content of protein and readily fermentable sugars makes especially food waste attractive for LA fermentation (Carmona-Cabello et al., 2020) (Table 2).

2.2. Pretreatment of lignocellulosic biowaste

The process overview for pretreatment and enzymatic hydrolysis aiming at fermentable sugars for LAB is shown in Fig. 1. Digestible food waste contains no lignin which makes it easy to hydrolyze enzymatically into fermentable sugars. Therefore lignin poor compounds such as seaweed is easier to hydrolyze (Thygesen et al., 2020) than lignin rich compounds such as wood and straw (Thomsen et al., 2008). In general, mechanical grinding of biowaste is needed to make it homogeneous. For lignocellulosic biowaste, pretreatment such as alkaline treatment, hydrothermal treatment (Thomsen et al., 2008), wet oxidation (Lissens et al., 2004), steam explosion and plasma treatment (Heiske et al., 2013) have been assessed to increase the enzymatic convertibility into fermentable sugars such as glucose and xylose. Pretreatment of lignocellulosic biomass has been reviewed recently by Sankaran et al. (2020). Pretreatment approaches aiming at LA fermentation includes acid hydrolysis (Hoheneder et al., 2021; Ouyang et al., 2020) and ionic liquid treatment (Yadav et al., 2021) (Table 3). The acid hydrolysis has the advantage of making enzymatic hydrolysis avoidable due to hydrolysis of cellulose and hemicellulose into monomeric sugars. Hydrothermal treatment is used to open the lignocellulosic structure by relocation or oxidation of lignin into surface droplets, which enables the enzymatic saccharification with cellulose and hemicellulose hydrolyzing enzymes (Rodrigues et al., 2015; Thomsen et al., 2008).

2.3. Enzymatic hydrolysis of lignocellulosic biowaste

2.3.1. Enzymatic hydrolysis mechanism

Production of fermentable sugars such as glucose, xylose, arabinose and mannose from cellulosic biowaste can be done by enzymatic hydrolysis with cellulases and hemicellulases (Kari et al., 2020). The cellulases includes *endo*-β-1,4-glucanases hydrolyzing amorphous cellulose so *exo*-β-1,4-glucanase can hydrolyze cellobiose from the cellulose chain ends. Finally, β-glucosidase hydrolyses the produced cellobiose into glucose. Hemicellulases such as *endo*-1,4-β-xylanase and β-xylosidase hydrolyses the xylan chains and acetyl groups with xylan esterase. In cases with pectin rich biowaste polygalactoronase is needed for liberation of galacturonic acid (Liu et al., 2016). α-L-arabinofuranosidase, β-mannanase and α-mannosidase are needed to remove sidechains containing arabinose to gain access to the xylan chains and liberate all the fermentable sugars. Although xylans are non-crystalline, many hemicellulases are thus required to break their complex chemical structure.

2.3.2. Enzymatic hydrolysis strategies aiming at LA fermentation

Yields of LA achieved in enzymatic hydrolysis and fermentation with different LAB are shown with focus on waste composition (Table 3) and with focus on process mechanisms and L and D isomers of LA (Table 4). For instance, addition of exogenous glucoamylases can enhance yield and productivities utilizing the indigenous microbiome during continuous fermentation of biowaste (Peinemann et al., 2019). Similarly, supplementation with α-amylase stimulated hydrolysis and enhanced LA

Table 3
Recent studies on lactic acid fermentation using biowaste streams and defined polysaccharides.

Waste	Composition	Microorganism	Key topic	Titer (g LA/L)	Productivity (g/L/h)	LA yield (g LA/g sugar)	Reference
Lignocellulosic wastes							
Spent sulfite liquor	Hemicellulose	*Enteroccus mundtii*	Simultaneous conversion	56.3 ± 5.4	0.53 ± 0.05	0.88 ± 0.02	(Hoheneder et al., 2021)
Alfalfa silage		*Bacillus subtillis*	Insilation	44.2	0.74		(Bai et al., 2020)
Wheat straw hydrolysate	Glucose + Xylose	*Bacillus coagulans*	Inhibitor tolerance	26.3	0–8 h: 0.91 8-104 h: 0.25	0.709	(Ouyang et al., 2020)
Ionic liquid treated rice straw	Glucose	*Lactobacillus plantarum*	Cellulase hydrolysis	37	0.77		(Yadav et al., 2021)
Starch and food derived wastes							
Apple waste	Starch/pectin		Anaerobic co-digestion	28	0.16	0.65	(Lian et al., 2020)
Potato waste	Starch		Anaerobic co-digestion	8.9		0.31	(Lian et al., 2020)
Food waste	Meat, rice, vegetables, tofu	*Bacillus, Enterococcus, Lactobasilus*	Salinity. Microbial community	30	0.62	0.75	(Li et al., 2021b)
Bakery waste + Yeast extract		*Bacillus coagulans*	Batch fermentation	59	2.4	0.84	(Alexandri et al., 2020)
Bakery waste + lucerne green juice				62	2.6	0.56	-
Bakery waste + Yeast extract		*Bacillus coagulans*	Continues (0.1 h^{-1})	46.9	4.7	0.69	-
Bakery waste + Yeast extract		*Bacillus coagulans*	Continues (0.2 h^{-1})	57.9	11.6	0.87	-
Bakery waste + lucerne green juice		*Bacillus coagulans*	Continues (0.1 h^{-1})	65.7	6.6	0.66	-
Bakery waste + lucerne green juice		*Bacillus coagulans*	Continues (0.2 h^{-1})	55	11.3	0.48	-

Table 4
Lactic production from municipal biowaste looking into LA isomer, fermentation conditions and LA yield.

Substrate	Microbes	Pretreatment	Isomer	pH	T (°C)	Titer (g LA/L)	Productivity (g/L/h)	Yield (g LA/g)	Reference
Cafeteria biowaste	*L. manihotivorans*	Blender grinding	L	5.0	30	48.7	–	1.11	(Ohkouchi and Inoue, 2006)
Bakery wastes	*L. casei* Shirota	Blender grinding	L	6.0	37	94.0	2.61	0.94	(Kwan et al., 2016)
Pulp mill residue	*L. coryniformis* tor	Cellic CTec2 hydrolysis	D	6.5	37	57	2.8	0.97	(de Oliveira Moraes et al., 2016)
Orange peel waste	*L. delbrueckii* CECT 286	Milling, Celluclast 1.5 l	D	5.8	37	45	0.63	0.86	(Bustamante et al., 2020)
–	*L. delbrueckii* CECT 286	Milling, Celluclast 1.5 l	D	5.8	40	41	2.35	0.88	(de la Torre et al., 2018)
–	*L. delbrueckii* CECT 5037	Milling, Celluclast 1.5 l	D	5.8	37	39	0.55	0.84	(Bustamante et al., 2020)
Household biowaste	Indigenous microbiome	Mechanical milling		5.0	37	29.7 ± 0.63	0.79 ± 0.05	–	(Probst et al., 2015)
Mixed baker biowaste	*Thermoanaerobacterium*	Blender grinding	L	5.5	55	78.4	1.63	0.18	(Yang et al., 2015)
Canteen biowaste	*Streptococcus* sp.	Blender grinding	L	6.0	35	66.5	3.38	0.33	(Demichelis et al., 2017)
			L	6.0	35	50.0	2.93	0.63	(Peinemann et al., 2019)
Household biowaste	*Bacillus coagulans*	Novozymes enzymes	L	6.0	52	60.0	2.84	0.71	(López-Gómez et al., 2019a)
–	*Bacillus coagulans*	Cellic CTec2 addition	L	6.0	52	68.0	–	0.65	(López-Gómez et al., 2020c)
–	*Bacillus coagulans*	Electrodialysis to remove D-LA	L	6.0	52	61.1	3.63	0.94	(López-Gómez et al., 2020a)
–	*Pediococcus acidilactici*	Biopulping	L	8.0	32.4	31.9 ± 0.4	–	0.74	(Zhang et al., 2021b)
Canteen biowaste	*Pediococcus acidilactici*	Blender grinding, micro-aeration	L	8.0	37	32.1 ± 0.5	–	0.76 ± 0.01	(Zhang et al., 2021a)

productivity by 70% compared to the control tests using food waste (Wang et al., 2016).

Apart from amylases, cellulose-degrading enzymes are also exploited to improve the process metrics of LA production. The enzymatic hydrolysis and subsequently, the LA yield was increased due to the addition of cellulase (20 U/g total solids (TS)) and β-glucosidase (10 U/g TS) (Tsapekos et al., 2020). In a different approach, (Zhang et al., 2021a) added markedly lower concentrations of β-glucosidase (2.5 U/g volatile solids (VS)) as sole exogenous enzymes coupled with micro-aeration to boost the activity of indigenous hydrolytic microbes. The combined treatment increased the concentration of soluble sugars by 77% compared to the non-treated biowaste and consequently, the LA process metrics (Table 3). Alternatively, a different approach to the addition of pure enzymes could be the application of filamentous fungi in a separate initial step (López-Gómez et al., 2020b). Specifically, previous studies focused on solid-state fermentation with *Aspergillus niger* (Wang et al., 2009) and co-fermentation with both *A. awamori* and *A. oryzae* (Kwan et al., 2016). These studies have shown positive results on LA production.

2.4. Utilization of animal wastes as protein source

Animal production waste including meat, hair, nails, blood and trimming bones are rich in protein and produced at large quantities at slaughterhouses (Toldrá et al., 2012). Animal waste has not been studied specifically as protein source for LAB cell mass production aiming at LA fermentation. Protein sources have been achieved by protease treatment of meat byproducts such as blood and collagen (Arihara et al., 2021). Addition of protein sources such as meat extract has been reported to increase the cell mass production and thus increase the LA productivity from 1.2 to 3.5 g/L/h (de la Torre et al., 2018). The implementation of animal waste is shown in Fig. 1.

3. Fermentation of biowaste to lactic acid focused on waste types

The recent studies on LA fermentation of biowaste have often been conducted using either fermentable sugars achieved from cellulose and hemicellulose in lignocellulosic waste or from starch in food biowaste. In both cases LA is produced by fermentation of sugars achieved by enzymatic or acidic hydrolysis as shown in Table 3 and Fig. 1.

3.1. Lignocellulosic biomass and derived extractives

The cellulosic wastes tested for fermentation has been achieved from sources such as sulphite liquor derived from wood pulp production (Hoheneder et al., 2021), wheat straw acid hydrolysate (Ouyang et al., 2020) and rice straw treated with ionic liquids (Yadav et al., 2021). These biomasses all consist of lignocellulose which were pre-treated and hydrolyzed into the fermentable sugars glucose, xylose, arabinose and mannose. These pre-treatments also resulted in formation of fermentation inhibitors such as furfural and 5-hydroxymethylfurfural by degradation of sugar oligomers hydrolyzed from hemicellulose and cellulose at elevated temperature (150–200 °C) (Thomsen et al., 2009). The benefit of the ionic liquid [EMIM][OAc] tested on rice straw was thus to make the recalcitrant cellulose part of the biomass enzymatic digestible at reduced temperature. The process mechanism is that the anions increased the solubility of lignin and hemicellulose without inhibitor formation resulting in increased enzymatic accessibility (Yadav et al., 2021).

The fermenting strain *Enteroccus mundtii* assessed on the sulfite liquor could despite the fermentation inhibitors ferment 99% of the sugars including glucose, mannose, galactose, xylose and arabinose into LA. The fermentation duration was 50 – 120 h resulting in 99% LA yield. The average productivity was 0.73 g/L/h with 3.18 g/L/h as maximum. A titer of 56 g LA/L was achieved using 100 g/L of the hydrolysate sugars (Hoheneder et al., 2021). *Bacillus coagulans* assessed on the wheat straw hydrolysate was made tolerant to phenolic fermentation inhibitors by adaptive evolution proved by complete xylose conversion and an increase in productivity from 0.28 g/L/h in the first fermentation cycle to 0.97 g/L/h in the third adaptation cycle. The explanation for the improved tolerance was up-regulated oxidoreductases and phenolic acid decarboxylase. In addition, the study confirmed that the enzymatic hydrolysis was inhibited, which was avoided by water washing of the solid cellulosic fraction. Simultaneous saccharification and fermentation showed a rapid depletion of glucose and xylose after 8 h (productivity = 0.91 g/L/h) followed by a phase limited by enzymatic hydrolysis terminating after 104 h with a productivity of 0.25 g/L/h (Ouyang et al., 2020). The enzymatic hydrolysis using ionic liquid treated wheat straw also gave a high glucose yield of 92% of the theoretical during a similar fermentation time with *Lactobacillus plantarum*. It had a similar productivity of 0.77 g/h/L but a lower titer of 37 g LA/L (Yadav et al., 2021). All the assessed lactic acid fermenting strains *E. mundtii*, *B. subtillis*, *B. coagulans* and *L. plantarum* could thereby conduct LA fermentation and the choice was thereby not critical for the LA productivity, which was 0.7 g/L/h on average while the titer increased versus the sugar concentration (Bai et al., 2020; Yadav et al., 2021) (Table 3).

3.2. Food waste containing starch and pectin

Food waste recently tested for LA fermentation are for a large extend starch related such as potato (Lian et al., 2020; Pradhan et al., 2021), wheat (Pradhan et al., 2021), apples (Lian et al., 2020) and bakery waste (Alexandri et al., 2020). The fermentation into LA requires enzymatic hydrolysis of the soluble polysaccharides into monosaccharides usind α-glucosidase while the soluble proteins are hydrolyzed with protease. These enzymes were produced in a mixed culture approach studied by Li et al. (2021b). However, for bread derived starch, enzymes were added including Ban 240l (*endo*-α-amylase) and Stargen™ 002 and Viscozyme for cellulose hydrolysis due to the lignocellulose content in the lucerne green juice (Alexandri et al., 2020).

The anaerobic co-digestion studied by Lian et al., (2020) using swine manure as inoculum could be done without enzyme addition for both apple and potato waste. The apple waste gave a higher LA concentration (28 g/L) than the potato waste (8.9 g/L) but the productivity was low (0.16 g/L/h). The use of a mixed community explained the low productivity with formation of side products such as butyric acid and acetic acid (Lian et al., 2020).

The Co-fermentation of food waste at saline conditions resulted in a stable microbial community of *Bacillus* sp., *Enterococcus* sp. and *Lactobacillus* sp. The study showed a LA productivity of 0.61 g/L/h and an achieved LA concentration of 30 g/L (Li et al., 2021b), which are similar to the results achieved on the lignocellulosic residues (Table 3) as explained due to similar fermentable sugars such as glucose and xylose achieved during the hydrolysis step.

The bakery waste batch fermentation resulted in a higher LA productivity of 2.4 g/L/h with *Bacillus coagulans* as fermenting strain with a titer of 62 g/L (Alexandri et al., 2020) compared with potato/apple derived starch (Li et al., 2021b; Lian et al., 2020). When lucerne green juice hydrolysate was added replacing yeast extract a 6 h lag phase took place but no significant change occurred in the LA titer demonstrating that it was useful as nitrogen supplement. The glucose was fully fermented as it is a base carbon source for many LAB (Yadav et al., 2021). However, the disaccharide content was not fully fermented confirming the need for enzymatic hydrolysis similar to findings by Pradhan et al., (2021). Shifting to continues fermentation increased the productivity to 11.6 g/L/h at a dilution rate of 0.2 h^{-1}. The increase was explained by an increase in cell density from 4200 to 9600 cells/μL (Table 3). Shifting to lucerne as nutrient source did not change the titer and productivity significantly. However, free glucose was observed when the dilution rate was increased to 0.2 h^{-1}. Despite this problem the results show the benefit in adding nutrient rich lucerne green juice to starch waste such as bread with a low protein content (Table 2) increasing the prospect of fermenting biowaste into LA.

4. Fermentation of biowaste to lactic acid with bacterial focus

4.1. Lactic acid bacteria and fermentation products

LA fermentation is a relatively quick microbially mediated process for the production of one of the two stereoisomers (L- and D- LA) or their racemic mixture. LAB have some specific phenotypic characteristics as their DNA have fewer GC base pairs compared to AT, are Gram-positive, are facultative anaerobes, do not form spores, tolerate acidic conditions (pH < 5), are immobile, and can ferment vast carbon sources having LA as end-product (Martinez et al., 2013). Despite the majority of LAB can optimally grow between 30 and 37 °C, some species are tolerant to temperatures up to 50 °C (Bosma et al., 2017).

Lactic acid bacteria are categorized into homo- and hetero-fermentative species. The principle of the homofermentative process is shown in Fig. 2a with lactic acid as the principal metabolite producing two mole LA and two mole ATP per mole glucose. The intermediate pyruvate is produced by glycolysis in the Embden–Meyerhof–Parnas pathway (Romano and Conway, 1996). In the heterofermentative process mentioned as the phosphoketolase pathway for C6 sugar, a mixture of 1 mol LA, 1 mol CO_2, and the by-product 1 mol ethanol are produced per mole glucose. For C5 sugar, 1 mol LA and 1 mol acetate are produced per mole xylose (Endo and Dicks, 2014) as shown in Fig. 2b. The heterofermentative species are divided into facultative and obligate types. The facultative type including *L. plantarum* and *L. pentosus* applies the homofermentative process when glucose is available and the phosphoketolase pathway when only C5 sugar is available. Finally, the obligate hetero-fermenters such as *L. sanfranciscensis* and *L. brevis* (Prückler et al., 2015) always uses the phosphoketolase pathway to dissimilate both C5 and C6 sugars.

4.2. Fermentation of biowaste to lactate

Considering that biowaste can contain a mixture of organic household wastes, restaurant wastes, garden wastes and industrial food wastes; understandably, the content of degradable organics including hexoses and pentoses such as hemicellulose, cellulose, and starch can vary greatly in the waste stream. Despite the high sugar content of biowaste (Table 2), the availability of free monomeric sugars is not high. In contrast, starch, cellulose, and hemicellulose represent a big share in the waste stream. Hence, the addition of exogenous enzymes or inoculation with hydrolytic microbes would be needed to hydrolyze the complex polysaccharides into oligomers and monosaccharides. Table 2 shows a rough estimate of the biowaste composition and justifies the need for hydrolysis of cellulose, hemicellulose, and pectin into fermentable sugars. Overall fermentation results on biowaste are outlined in Table 4 assessing a range of LAB bacteria.

4.2.1. Challenges for increased process metrics

Biowaste has a high content of food residues and contains a surplus of nutrients (e.g., nitrogen, phosphorus, magnesium, potassium, calcium) improving microbial growth and subsequently the LA production (Kwan et al., 2017; López-Gómez et al., 2020b). However, biowaste can be quite heterogeneous as mentioned, and has also different characteristics in terms of pH, salinity, and inhibitors (e.g., ethanol) creating stress conditions under which the homofermentative strains can shift the metabolism towards formic acid by the action of pyruvate-formate lyase (Martinez et al., 2013; Mayo et al., 2010). While LAB species could markedly proliferate in the biowaste under non-controlled conditions (Probst et al., 2013), antagonism between different bacteria for sugars utilization creates a non-ideal environment for LA optimization.

4.2.2. Exploitation of native microbiome

Natural inhabitants in the fresh biowaste provide the initial seed and within the native microbiome, lactobacilli can thus proliferate and dominate the community. In this frame, Probst et al., (2013) found that the heterolactic *Lactobacillus brevis*, homolactic *Lactobacillus plantarum*, and their closest genera accounted for more than 70% of the community. *L. brevis* are heterofermentative LAB with the ability to ferment xylose (Fig. 2), low ethanol tolerance, and low performance at acidic conditions (Bosma et al., 2017; Cui et al., 2011). On the other hand, the homo-fermentative *L. plantarum* spp. are found in numerous fermented food products (Behera et al., 2018) and their dominance in biowaste native flora has a great impact on LA production. Despite the generally low potential of LAB to hydrolyze complex sugars, *L. plantarum* has high amylolytic capacity favoring their presence in starchy food waste streams (i.e., potato, corn, wheat, rice) to perform simultaneous hydrolysis and fermentation of LA (John et al., 2007). For example, LAB with high amylolytic capacity can adapt their metabolism to starch degradation during continuous conversion and depletion of C5 and C6 sugars (Dreschke et al., 2015). Moreover, *L. plantarum* species can grow well over a wide pH range favoring their establishment in biowaste (Sakai et al., 2000).

Furthermore, the homo-fermentative genera of *Pediococcus* and *Streptococcus* are also well-known LA cell factories (Carr et al., 2002). At first, *Pediococcus* are proliferated during the food waste decomposition (Jiang et al., 2020; Lim et al., 2020). In the literature, *Pediococcus acidilactici* was successfully utilized since it can quickly grow on food waste producing high titer of LA and inhibiting the formation of acetic acid by other strains (Tran et al., 2019). Next, *Streptococcus* can naturally dominate biowaste related food waste as it can secrete extracellular amylases to hydrolyze starch and convert it directly to LA (Demichelis et al., 2017). This ability makes it to a good candidate for simultaneous saccharification and fermentation with high yields and productivities (Pleissner et al., 2017).

4.2.3. Pure or open culture operation

Open culture fermentation can be used as approach, which has the characteristics of not being pre-sterilized and use a naturally evolved mixed culture in the fermentation. Although open culture fermentations have some unique characteristics such as no need for sterilization and exploitation of indigenous microbiomes, by-products such as ethanol, acetic, propionic, and butyric acids are formed reducing the potential for achieving high LA yield and titer. At non-sterile conditions, other acidogenic native strains can proliferate and either compete for sugars utilization (Zhang et al., 2021b) or use LA as a carbon source (Wang et al., 2016) for by-product formation.

On the contrary, sterilization of biowaste could theoretically be applied to deactivate the competing microbes. On this topic, autoclavation was examined as a pretreatment technique to release monosaccharides and simultaneously, eliminate the activity of indigenous microbes before the inoculation with *L. delbrueckii* (Tsapekos et al., 2020). Nevertheless, sterilization led to a markedly lower yield (0.22 g/g total sugars) compared to the non-autoclaved treatment (0.66 g/g total sugars) revealing the robustness of mixed culture fermentation compared to pure culture fermentation. The robustness of the LA fermentation process makes logistics (collection, storage, transportation etc.) of the biowaste less critical. Despite the potential for achieving high efficiency during mixed culture fermentation, the risk of producing a racemic mixture of lactate is increased. The L- and D- enantiomers are produced based on LAB's ability to encode L- and D-lactate dehydrogenase, respectively (Bosma et al., 2017). L-lactic acid fermentation is currently the dominant approach with only a few D-LA studies (Table 4).

4.2.4. D-Lactic acid fermentation

D-LA has been produced by fermentation of sugars from enzymatic hydrolyzed pulp mill residue and orange peel waste using *L. coryniformis* (de Oliveira Moraes et al., 2016) and *L. delbrueckii* (Bustamante et al., 2020; de la Torre et al., 2018), respectively. Fermentable sugars were produced by enzymatic hydrolysis using cellulase enzyme cocktails (Celluclast/Cellic CTec2). The orange peels hydrolysis resulted in equal concentrations of glucose and the sum of fructose + galactose as fermentable sugars. The effect on nitrogen source was studied by de la Torre et al. (2018) including meat extract (ME), yeast extract (YE) and corn stover liquor (CSE). Effective sugar conversion was achieved with at least 1.2 g/L nitrogen supplement. The fraction of converted fructose + galactose was for ME 95%, for YE 87% and for CSL 67% resulting in cell mass concentrations of 7.48, 7.35 and 4.78 g/L, respectively. The achieved LA productivities were 3.4, 3.3 and 2.4 g/L/h corresponding to similar biomass based LA productivities in the range of 0.46 – 0.49 h^{-1}. This indicates that the fermentation rate was limited by the cell mass content similar to results on L-LA fermentation and thus increased proportional to the cell mass (Alexandri et al., 2020). The achieved LA concentrations were in the range of 39 – 57 g/L with yields of 0.84 – 0.97 g LA/g sugar. These results are similar to what is achieved for the production of L-LA (Bustamante et al., 2020; de Oliveira Moraes et al., 2016).

4.2.5. Opportunities to overcome the limitations

To round up, microbial diversity (i.e., indigenous microbes) and dynamicity (i.e., inoculation with pure strains) highly affect optical purity, yield, titer, and productivity. As alternative approaches to

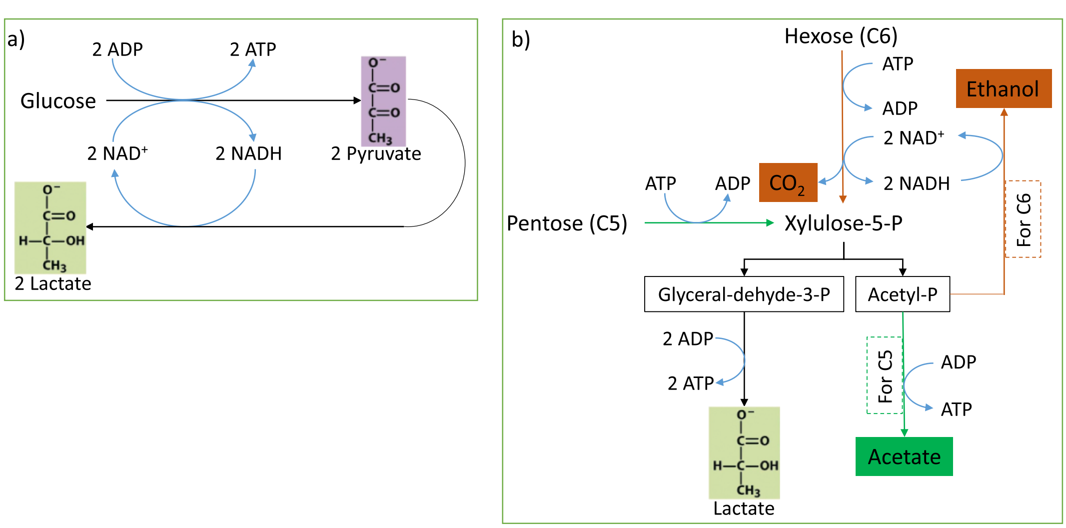


Fig. 2. Lactic acid production for homofermentative LAB fermenting glucose (a) and heterofermentative LAB fermenting C_6 sugars and C_5 sugars with ethanol and acetate as byproducts. The C_6 and the C_5 metabolism are in brown and green, respectively.

manipulate the microbiome and optimize process feasibility could be the controlled bio-waste storage time and logistics (Zhang et al., 2021a), pretreatment techniques (López-Gómez et al., 2020a; Yousuf et al., 2018), and inoculation with LAB after evolutionary or stepwise adaptation (Dreschke et al., 2015; Yang et al., 2015). The reported studies indicate that the LAB cell mass was limiting for both L-LA fermentation (Alexandri et al., 2020) and D-LA fermentation (de la Torre et al., 2018). Prospects for effective LA fermentation are improved considering implementation of sustainable N-sources such as corn stover liquor (de la Torre et al., 2018), green seaweed (Bentil et al., 2019) and slaughterhouse waste (Arihara et al., 2021).

5. Downstream processing

Downstream processing used to purify fermentation broth filtration approaches, reactive distillation, and molecular distillation. Results on the purification are shown in Table 5 and indicated in Fig. 1.

5.1. Downstream separation process for lactic acid recovery

Downstream separation is a major factor to be considered for a cost-effective LA production which usually represents 20–50% of the operation costs of the process (Alves de Oliveira et al., 2018). Several studies have been dedicated to improving the LA downstream separation from biowaste based fermentation aiming to reduce production cost and improve sustainability metrics.

Noteworthy, due to the physicochemical characteristics of the biowaste, the synthesis and design of the downstream process for the recovery and purification of LA can be a quite challenging separation task. LA has to be recovered from a highly diluted fermentation broth composed of suspended solids, cell biomass, residual sugars (e.g., glucose, xylose, fructose), bio-macromolecules (e.g., proteins, lipids, polysaccharides, nucleic acids), other carboxylic acids (e.g., formic, acetic, succinic, propionic, butyric acids), alcohols (ethanol, 1-propanol) and ions (e.g., K^+, Na^+, Ca^{2+}, Mg^{2+}).

To accomplish this separation task, many downstream process design alternatives have been described in the literature (Komesu et al., 2017b). In general, the conventional process for LA recovery and purification consists of filtration and centrifugation for biomass removal followed by neutralization and precipitation of the LA with calcium hydroxide yielding calcium lactate. Following this, a filtration process is used to recover the calcium lactate and sulfuric acid is used to dissolve the calcium lactate formed and recover the LA. This step generates large amounts of calcium sulfate ($CaSO_4$) that need to be regenerated into $Ca(OH)_2$ and H_2SO_4 or used industrially for production of gypsum boards. Alternatively, LA can be recovered by liquid-liquid extraction or ion exchange from the inorganic salt. Either solvent extraction, separation with membranes, evaporation, crystallization, or distillation processes are applied to concentrate the LA recovered from the previous step. At last, chromatography and ion exchange, are required for the removal of impurities.

Table 5
Lactic acid recovery and purity achieved from fermented biowaste after downstream separation.

LA ferment. substrate	Purification strategy	LA recovery	Purity	Reference
Downstream separation processing				
Municipal biopulp	Centrifugation + ultrafiltration + distillation → Ion exchange + distillation	75.7%	72.5%	(Alvarado-Morales et al., 2021)
Municipal biopulp	Centrifugation + ultrafiltration + distillation → Nanofiltration	82.0%	65.0%	(Alvarado-Morales et al., 2021)
Food waste	Nanofiltration → Mono + bipolar electrodialysis	38%	99.7%	(Pleissner et al., 2017)
Reactive distillation			Conc.	
Esterification between ethanol and lactic acid. Catalytical approach		99.94%	34 g/L	(Komesu et al., 2015)
Sugarcane	Esterification between ethanol and lactic acid → Ester hydrolysis	99.95%		(Mandegari et al., 2017)
Molecular distillation + Novel approaches		Extraction efficiency		
Molecular distillation and adiabatic crystallisation		95%		(Van Breugel et al., 2000)
ELM extraction		99%		(Garavand et al., 2018)

For instance, Alvarado-Morales et al. (2021) investigated two downstream processes to recover LA from municipal biopulp based fermentation. A pre-purification step such as centrifugation, ultrafiltration, and activated carbon was in common to the two methods investigated. After the pre-purification step, ion exchange and vacuum distillation were applied in the first method resulting in LA recovery of 75.7 ± 1.5 % and purity of 72.5 ± 2.0 %, respectively. In the second method, a nanofiltration unit was included after the pre-purification step, which resulted in a higher LA purity of 82.0 ± 1.5 % but reducing the recovery to 65.0 ± 1.5 %.

On the other hand, Pleissner et al. (2017) recovered LA from the fermentation of food waste using micro- and nano-filtration units followed by mono- and bi-polar electrodialysis to concentrate the LA and to separate it from the salts. However, the concentration of ions was still high, and then an anion- and cation- exchange step was necessary which resulted in a decrease of Na^+, K^+, and Cl^- ions to less than 0.01 g/L but also LA concentration was decreased by 70% (54.1 g/L) with respect to its concentration after the electrodialysis step (171 g/L). Finally, to increase LA concentration, evaporation was applied resulting in a final LA concentration of 702 g/L with a recovery of 38% with respect to the LA present in the fermentation broth; clearly, a limitation of this method as 62% of the product was lost. On the other hand, the optical purity of the final product was 99.7% fulfilling the quality requirements for PLA synthesis. The advantages and disadvantages of these separation techniques and the combination of them are very well documented and reviewed in the literature (Komesu et al., 2017b).

Separation technologies for purification such as reactive distillation and molecular distillation have been implemented using emulsion liquid membranes (ELM), liquid membranes in Taylor flow and green ionic liquid ELM (Garcia-Aguirre et al., 2020; Komesu et al., 2017c; Li et al., 2021a; Mai et al., 2018; Murali et al., 2017). The combination of these with well-established separation techniques have opened a new window for design and synthesis of more sustainable and energetically efficient downstream separation processes for LA recovery.

5.2. Reactive distillation

Reactive distillation is applied specifically to reversible chemical reactions in the liquid phase, in which reaction equilibrium limits the conversion of reactants. Reactive distillation has been proposed as a promising reactive-separation process for the recovery of lactic acid with high recovery and productivity. The LA recovery involves a reversible reaction presented in Eq. (1). The forward reaction represents esterification of LA into ethyl acetate while the reverse reaction represents hydrolysis to LA in the presence of an acidic catalyst.

$$Lactic\ acid + ethanol \overset{catalyst}{\rightleftarrows} ethyl\ actate + H_2O \quad (1)$$

Homogeneous catalysts often employed are sulfuric acid and anhydrous hydrogen chloride. However, ion-exchange resins can also be used offering advantages such as low corrosion, ease of separation from the reactive mixture, no side reactions and can be re-used over the homogenous catalysts. Alcohols such as methanol, ethanol, 2-propanol and butanol can be used in the esterification step. The advantage of using ethanol is that it can be produced from renewable resources, although butanol and methanol are more attractive options from an economical point of view. The esterification with ethanol or 2-propanol is more expensive since a mass separation agent is needed to break the alcohol/water azeotrope.

Komesu et al (2015) investigated the esterification reaction between ethanol and lactic acid in a reactive distillation column. The ethyl lactate yield attained was 99.94% under the following conditions: ethanol/LA molar ratio = 18.4, reboiler temperature = 125 °C and catalyst loading = 6 % (w/w). The lactic acid concentration obtained in the hydrolysis step was 34 g/L being 3 times higher than the initial concentration. However, in recent literature the studies for LA recovery are scarce from first and second-generation substrates-based-fermentation using reactive distillation. However, simulation approaches using commercial simulators to model/simulate the recovery and purification of lactic acid from second-generation feedstocks-based fermentation have been investigated.

Daful et al (2016) investigated the environmental performance of lactic acid produced from lignocellulosic biomass and petrochemical sources using a life cycle approach. Lactic acid from the fermentation broth was purified via reactive distillation columns. Likewise, Gezae Daful and Görgens (2017) performed a techno-economic analysis and environmental impact assessment of a process to produce LA from lignocellulosic feedstocks. The purification and recovery of LA from the fermentation broth consisted of a train of reactive distillation columns including esterification with ethanol and hydrolysis, respectively. Mandegari et al. (2017) investigated the co-production of LA and ethanol from sugarcane *via* a multicriteria analysis based on economic evaluation, energy assessment, and environmental life cycle assessment. Reactive distillation was applied for LA recovery. LA produced from the esterification column was converted to lactic acid ethyl ester by the addition of ethanol, which was further separated by distillation. Pure LA (>99.5 % (w/w)) was subsequently recovered by hydrolysis of the ester in a second reactive distillation column.

5.3. Molecular distillation

Molecular distillation or short path distillation is a nonconventional unit operation of diffusional mass transfer employed for separation of homogeneous liquid mixtures with → low volatility, high molecular mass, and high thermosensitivity. It is considered as a special case of evaporation where steam is generated on the liquid surface with the difference that there is practically no return of gaseous molecules to the liquid phase (no vapor-liquid equilibrium). This is achieved by setting the hot evaporation surface and the cold condensation surface closer to each other than the mean free path of the evaporated molecules. Therefore, the evaporated molecules easily reach the condenser, since the route is unobstructed. The distance between the evaporating and condensing surfaces is typically between 1 and 5 cm. In addition, as the process does not involve the use of a solvent as in extractive distillation, the product material is not polluted and no further purification is needed (Komesu et al., 2017c).

The industrial interest in the purification of LA by molecular distillation has been demonstrated by many published patents. Purac Biochem published a method for the industrial-scale purification of LA using molecular distillation and adiabatic crystallization to obtain a 95% pure lactic acid (Van Breugel et al., 2000). Brussels Biotech published a process comprising the following steps: pretreating a diluted solution of lactic acid, concentrating and re-concentrating the diluted solution, and distilling the lactic acid using molecular distillation to obtain the purified lactic acid (Van Gansbeghe et al., 2002). Archer Daniels Midland Company developed a method comprising two-step distillation processes (reactive and molecular distillation) for recovering lactic acid and ethyl lactate (Leboreiro, 2016).

5.4. Emerging extraction technologies

Currently, some new extraction techniques, such as ELM and liquid membrane in Taylor flow, have been successfully used to recover LA from fermentation broth. During the ELM based separation processes, ELM is first obtained upon emulsification of two immiscible phases (organic phase and internal phase) and then dispersing ELM into a third phase i.e. continuous feed phase by stirring for the extraction of low concentrated solute molecules (Li et al., 2021a).

The ELM method has been successfully applied to recover organic acids such as lactic acid from fermentation broth with an extraction efficiency of up to 99% under suboptimal conditions (Garavand et al., 2018). Innovative development of ELM technology is the use of green solvents (or vegetable oils) and ionic liquids to formulate the organic phase. Kumar et al., (2018) investigated the recovery of LA through green emulsion ionic liquid membrane using rice bran oil as a green solvent. Under the optimal process parameters, the LA extraction efficiency was about 90%. Advantages of the ELM method such as large mass transfer area, ease of operation, high extraction efficiency for low solute concentration, and low energy requirements make this technique a promising option to develop more cost-effective downstream processes with less environmental impact. Nevertheless, the poor stability of the ELM technique is the major drawback for large-scale industrial implementation. In this case, liquid membrane in Taylor flow is a novel technology that aims to overcome the stability problems of emulsion systems while keeping the advantages of ELM (Pérez and Fontalvo, 2019).

Pérez et al. (2019) developed a fermentation system for lactic acid production based on a model for a hybrid liquid membrane in Taylor flow. Compared with the traditional batch fermentation, the fermentation time of the hybrid system was decreased by 7 h which is a significant improvement and the productivity and biomass concentration were increased by 2.58 g/L/h and 2.70 g/L, respectively. Unfortunately, this model does not take into account the molecular toxicity of the extractants, and thus the liquid membrane in Taylor flow technology is still in the experimental stage.

Because second generation-lactic acid fermentation is a mixture that is more complex than commercial lactic acid feedstock, due to the presence of residual sugars and other organic acids, the performance of these emerging separation process technologies may be influenced as reactive distillation is affected by the feed composition. In addition, the presence of lipids may adversely affect the reactive distillation process because they can compete with lactic acid in the esterification and hydrolysis reactions, or have a negative effect on the emulsification of two immiscible phases in the ELM process. Therefore, new experimental studies on lactic acid recovery from bio pulp based-fermentation broth with these novel technologies are required to develop more efficient and economically attractive downstream separation processes for industrial applications.

6. Conclusion

Municipal organic waste consists of food waste containing starch and protein and a lignocellulosic fraction of mainly cellulose and hemicellulose. Without proper treatment it is difficult to ferment to lactic acid due to lack of enzymatic hydrolysis of the lignocellulose. The food waste is easier to ferment as it is less recalcitrant. Several lactic acid bacteria can produce the hydrolytic enzymes needed for fermentation process. In cases of starch waste, nitrogen-rich additives such as lucerne green juice could thus replace expensive nutrients such as yeast extract. For downstream processing, reactive distillation gave high purity needed in production of polylactic acid.

CRediT authorship contribution statement

Anders Thygesen: Conceptualization, Investigation, Formal analysis, Writing - original draft. **Panagiotis Tsapekos:** Conceptualization, Writing - original draft. **Merlin Alvarado-Morales:** Conceptualization, Writing - original draft. **Irini Angelidaki:** Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Ahmad, A., Banat, F., Taher, H., 2020. A review on the lactic acid fermentation from low-cost renewable materials: Recent developments and challenges. Environ. Technol. Innov. 20, 101138. https://doi.org/10.1016/j.eti.2020.101138.

Ajala, E.O., Olonade, Y.O., Ajala, M.A., Akinpelu, G.S., 2020. Lactic Acid Production from Lignocellulose – A Review of Major Challenges and Selected Solutions. Chem. Bio. Eng. Rev. 7 (2), 38–49. https://doi.org/10.1002/cben.v7.210.1002/cben.201900018.

Alexandri, M., Schneider, R., Mehlmann, K., Venus, J., 2019. Recent advances in d-lactic acid production from renewable resources: Case studies on agro-industrial waste streams. Food Technol. Biotechnol. 57, 293–304. https://doi.org/10.17113/ftb.57.03.19.6023.

Alexandri, M., Blanco-Catalá, J., Schneider, R., Turon, X., Venus, J., 2020. High L(+)-lactic acid productivity in continuous fermentations using bakery waste and lucerne green juice as renewable substrates. Bioresour. Technol. 316, 123949. https://doi.org/10.1016/j.biortech.2020.123949.

Alvarado-Morales, M., Kuglarz, M., Tsapekos, P., Angelidaki, I., 2021. Municipal biopulp as substrate for lactic acid production focusing on downstream processing. J. Environ. Chem. Eng. 9 (2), 105136. https://doi.org/10.1016/j.jece:2021.105136.

Alves de Oliveira, R., Komesu, A., Vaz Rossell, C.E., Maciel Filho, R., 2018. Challenges and opportunities in lactic acid bioprocess design—From economic to production aspects. Biochem. Eng. J. 133, 219–239. https://doi.org/10.1016/j.bej.2018.03.003.

Angelidaki, I., Heinfelt, A., Ellegaard, L., 2006. Enhanced biogas recovery by applying post-digestion in large-scale centralized biogas plants. Water Sci. Technol. 54 (2), 237–244.

Arihara, K., Yokoyama, I., Ohata, M., 2021. Bioactivities generated from meat proteins by enzymatic hydrolysis and the Maillard reaction. Meat Sci. 180, 108561. https://doi.org/10.1016/j.meatsci.2021.108561.

Bai, J., Xu, D., Xie, D., Wang, M., Li, Z., Guo, X., 2020. Effects of antibacterial peptide-producing *Bacillus subtilis* and *Lactobacillus buchneri* on fermentation, aerobic stability, and microbial community of alfalfa silage. Bioresour. Technol. 315, 123881. https://doi.org/10.1016/j.biortech.2020.123881.

Behera, S.S., Ray, R.C., Zdolec, N., 2018. *Lactobacillus plantarum* with Functional Properties: An Approach to Increase Safety and Shelf-Life of Fermented Foods. Hindawi BioMed Res. Int. 9361614 https://doi.org/10.1143/JJAP.47.2152.

Bentil, J.A., Thygesen, A., Lange, L., Mensah, M., Meyer, A.S., 2019. Green seaweeds (*Ulva fasciata* sp.) as nitrogen source for fungal cellulase production. World J. Microbiol. Biotechnol. 35, 82. https://doi.org/10.1007/s11274-019-2658-1.

Bosma, E.F., Forster, J., Nielsen, A.T., 2017. *Lactobacilli* and *pediococci* as versatile cell factories – Evaluation of strain properties and genetic tools. Biotechnol. Adv. 35 (4), 419–442. https://doi.org/10.1016/j.biotechadv.2017.04.002.

Bustamante, D., Tortajada, M., Ramón, D., Rojas, A., 2020. Production of D-lactic acid by the fermentation of orange peel waste hydrolysate by lactic acid bacteria. Fermentation 6, 10–12. https://doi.org/10.3390/fermentation6010001.

Carmona-Cabello, M., García, I.L., Sáez-Bastante, J., Pinzi, S., Koutinas, A.A., Dorado, M.P., 2020. Food waste from restaurant sector – Characterization for biorefinery approach. Bioresour. Technol. 301, 122779. https://doi.org/10.1016/j.biortech.2020.122779.

Carr, F.J., Chill, D., Maida, N., 2002. The lactic acid bacteria: A literature survey. Crit. Rev. Microbiol. 28 (4), 281–370. https://doi.org/10.1080/1040-840291046759.

Cui, F., Li, Y., Wan, C., 2011. Lactic acid production from corn stover using mixed cultures of *Lactobacillus rhamnosus* and *Lactobacillus brevis*. Bioresour. Technol. 102 (2), 1831–1836. https://doi.org/10.1016/j.biortech.2010.09.063.

Daful, A.G., Haigh, K., Vaskan, P., Görgens, J.F., 2016. Environmental impact assessment of lignocellulosic lactic acid production: Integrated with existing sugar mills. Food Bioprod. Process. 99, 58–70. https://doi.org/10.1016/j.fbp.2016.04.005.

de la Torre, I., Ladero, M., Santos, V.E., 2018. Production of D-lactic acid by *Lactobacillus delbrueckii* ssp. delbrueckii from orange peel waste: techno-economical assessment of nitrogen sources. Appl. Microbiol. Biotechnol. 102 (24), 10511–10521. https://doi.org/10.1007/s00253-018-9432-4.

de Oliveira Moraes, A., Ramirez, N.I.B., Pereira, N., 2016. Evaluation of the fermentation potential of pulp mill residue to produce d(−)-lactic acid by separate hydrolysis and fermentation using *Lactobacillus coryniformis* subsp. torquens. Appl. Biochem. Biotechnol. 180 (8), 1574–1585. https://doi.org/10.1007/s12010-016-2188-3.

Demichelis, F., Pleissner, D., Fiore, S., Mariano, S., Navarro Gutiérrez, I.M., Schneider, R., Venus, J., 2017. Investigation of food waste valorization through sequential lactic acid fermentative production and anaerobic digestion of fermentation residues. Bioresour. Technol. 241, 508–516. https://doi.org/10.1016/j.biortech.2017.05.174.

Dreschke, G., Probst, M., Walter, A., Pümpel, T., Walde, J., Insam, H., 2015. Lactic acid and methane: Improved exploitation of biowaste potential. Bioresour. Technol. 176, 47–55. https://doi.org/10.1016/j.biortech.2014.10.136.

EC. Council. 2018. Establishing best available techniques (BAT) conclusions for waste treatment, under directive 2010/75/EU of the European Parliament and of the Council.

EC. Council. 1999. EC. Council Directive 1999/31/EC on the Landfill of Waste.

Endo, A., Dicks, L.M.T., 2014. In: Lactic Acid Bacteria: Biodiversity and Taxonomy. John Wiley & Sons, Ltd, Chichester, UK, pp. 13–30. https://doi.org/10.1002/9781118655252.ch2.

Garavand, F., Razavi, S.H., Cacciotti, I., 2018. Synchronized extraction and purification of L-lactic acid from fermentation broth by emulsion liquid membrane technique. J. Dispers. Sci. Technol. 39 (9), 1291–1299. https://doi.org/10.1080/01932691.2017.1396225.

Garcia-Aguirre, J., Alvarado-Morales, M., Fotidis, I.A., Angelidaki, I., 2020. Up-concentration of succinic acid, lactic acid, and ethanol fermentations broths by forward osmosis. Biochem. Eng. J. 155, 107482. https://doi.org/10.1016/j.bej.2019.107482.

Gezae Daful, A., Görgens, J.F., 2017. Techno-economic analysis and environmental impact assessment of lignocellulosic lactic acid production. Chem. Eng. Sci. 162, 53–65. https://doi.org/10.1016/j.ces.2016.12.054.

Ghaffar, T., Irshad, M., Anwar, Z., Aqil, T., Zulifqar, Z., Tariq, A., Kamran, M., Ehsan, N., Mehmood, S., 2014. Recent trends in lactic acid biotechnology: A brief review on production to purification. J. Radiat. Res. Appl. Sci. 7 (2), 222–229. https://doi.org/10.1016/j.jrras.2014.03.002.

Hamad, K., Kaseem, M., Ayyoob, M., Joo, J., Deri, F., 2018. Polylactic acid blends: The future of green, light and tough. Prog. Polym. Sci. 85, 83–127. https://doi.org/10.1016/j.progpolymsci.2018.07.001.

Hanssen, O.J., Syversen, F., Stø, E., 2016. Edible food waste from Norwegian households—Detailed food waste composition analysis among households in two different regions in Norway. Resour. Conserv. Recycl. 109, 146–154.

Heiske, S., Schultz-Jensen, N., Leipold, F., Schmidt, J.E., 2013. Improving Anaerobic Digestion of Wheat Straw by Plasma-Assisted Pretreatment. J. At. Mol. Phys. 2013, 1–7. https://doi.org/10.1155/2013/791353.

Hoheneder, R., Fitz, E., Bischof, R.H., Hoheneder, R., Russmayer, H., Ferrero, P., Peacock, S., Sauer, M., 2021. Efficient conversion of hemicellulose sugars from spent sulfite liquor into optically pure L-lactic acid by *Enterococcus mundtii*. Bioresour. Technol. 333, 125215.

Jantasee, S., Kienberger, M., Mungma, N., Siebenhofer, M., 2017. Potential and assessment of lactic acid production and isolation – a review. J. Chem. Technol. Biotechnol. 92 (12), 2885–2893. https://doi.org/10.1002/jctb.2017.92.issue-1210.1002/jctb.5237.

Jiang, J., Yang, B., Ross, R.P., Stanton, C., Zhao, J., Zhang, H., Chen, W., 2020. Comparative genomics of *Pediococcus pentosaceus* isolated from different niches reveals genetic diversity in carbohydrate metabolism and immune system. Front. Microbiol. 11, 1–22. https://doi.org/10.3389/fmicb.2020.00253.

John, R.P., Nampoothiri, K.M., Pandey, A., 2007. Fermentative production of lactic acid from biomass: An overview on process developments and future perspectives. Appl. Microbiol. Biotechnol. 74 (3), 524–534. https://doi.org/10.1007/s00253-006-0779-6.

Kari, J., Schiano-Di-Cola, C., Hansen, S.F., Badino, S.F., Sørensen, T.H., Cavaleiro, A.M., Borch, K., Westh, P., 2020. A steady-state approach for inhibition of heterogeneous enzyme reactions. Biochem. J. 447, 1971–1982. https://doi.org/10.1042/BCJ20200083.

Kaza, S., Yao, L.C., Bhada-Tata, P., Van Woerden, F., 2018. What a waste 2.0. A global snapshot of solid waste management to 2050. The World Bank. Urban development. World Bank, Washington, DC.

Khoshnevisan, B., Tsapekos, P., Zhang, Y., Valverde-Pérez, B., Angelidaki, I., 2019. Urban biowaste valorization by coupling anaerobic digestion and single cell protein production. Bioresour. Technol. 290, 121743. https://doi.org/10.1016/j.biortech.2019.121743.

Komesu, A., Martinez, P.F.M., Lunelli, B.H., Filho, R.M., Maciel, M.R.W., 2015. Lactic acid purification by reactive distillation system using design of experiments. Chem. Eng. Process. Process Intensif. 95, 26–30. https://doi.org/10.1016/j.cep.2015.05.005.

Komesu, A., de Oliveira, J.A.R., da Martins, L.H.S., Wolf Maciel, M.R., Maciel Filho, R., 2017a. Lactic Acid Production to Purification: A Review. BioResources 12, 4364–4383. https://doi.org/10.15376/biores.12.2.komesu.

Komesu, A., Wolf Maciel, M.R., Maciel Filho, R., 2017b. Separation and purification technologies for lactic acid – A brief review. BioResources 12, 3. https://doi.org/10.15376/biores.12.3.6885-6901.

Komesu, A., Wolf Maciel, M.R., Rocha de Oliveira, J.A., da Silva Martins, L.H., Maciel Filho, R., 2017c. purification of lactic acid produced by fermentation: focus on non-traditional distillation processes. Sep. Purif. Rev. 46 (3), 241–254. https://doi.org/10.1080/15422119.2016.1260034.

Kowalewska, A., Nowacka, M., 2020. Supramolecular interactions in hybrid polylactide blends-the structures, mechanisms and properties. Molecules 25 (15), 3351. https://doi.org/10.3390/molecules25153351.

Kumar, A., Thakur, A., Panesar, P.S., 2019. Lactic acid and its separation and purification techniques: A review. Reviews Env. Sci. Biotechnol. 18, 823–853. https://link.springer.com/article/10.1007/s11157-019-09517-w.

Kumar, A., Thakur, A., Panesar, P.S., 2018. Lactic acid extraction using environmentally benign green emulsion ionic liquid membrane. J. Clean. Prod. 181, 574–583. https://doi.org/10.1016/j.jclepro.2018.01.263.

Kwan, T.H., Hu, Y., Lin, C.S.K., 2016. Valorisation of food waste via fungal hydrolysis and lactic acid fermentation with *Lactobacillus casei* Shirota. Bioresour. Technol. 217, 129–136. https://doi.org/10.1016/j.biortech.2016.01.134.
Kwan, T.H., Vlysidis, A., Wu, Z., Hu, Y., Koutinas, A., Lin, C.S.K., 2017. Lactic acid fermentation modelling of *Streptococcus thermophilus* YI-B1 and *Lactobacillus casei* Shirota using food waste derived media. Biochem. Eng. J. 127, 97–109. https://doi.org/10.1016/j.bej.2017.08.012.
Leboreiro, J., 2016. Novel lactic acid recovery process. Patent EP3166920A4. European Patent Office.
Li, C., Gao, M., Zhu, W., Wang, N., Ma, X., Wu, C., Wang, Q., 2021a. Recent advances in the separation and purification of lactic acid from fermentation broth. Process Biochem. 104, 142–151. https://doi.org/10.1016/j.procbio.2021.03.011.
Li, X., Sadiq, S., Zhang, W., Chen, Y., Xu, X., Abbas, A., Chen, S., Zhang, R., Xue, G., Sobotka, D., Makinia, J., 2021b. Salinity enhances high optically active L-lactate production from co-fermentation of food waste and waste activated sludge: Unveiling the response of microbial community shift and functional profiling. Bioresour. Technol. 319, 124124. https://doi.org/10.1016/j.biortech.2020.124124.
Lian, T., Zhang, W., Cao, Q., Wang, S., Dong, H., 2020. Enhanced lactic acid production from the anaerobic co-digestion of swine manure with apple or potato waste via ratio adjustment. Bioresour. Technol. 318, 124237. https://doi.org/10.1016/j.biortech.2020.124237.
Lim, Y.H., Foo, H.L., Loh, T.C., Mohamad, R., Rahim, R.A., 2020. Rapid evaluation and optimization of medium components governing tryptophan production by pediococcus acidilactici tp-6 isolated from Malaysian food via statistical approaches. Molecules 25 (4), 779. https://doi.org/10.3390/molecules25040779.
Lissens, G., Thomsen, A.B., De Baere, L., Verstraete, W., Ahring, B.K., 2004. Thermal wet oxidation improves anaerobic biodegradability of raw and digested biowaste. Environ. Sci. Technol. 38 (12), 3418–3424.
Liu, M., Silva, D.A.S., Fernando, D., Meyer, A.S., Madsen, B., Daniel, G., Thygesen, A., 2016. Controlled retting of hemp fibres: Effect of hydrothermal pre-treatment and enzymatic retting on the mechanical properties of unidirectional hemp/epoxy composites. Compos. Part A Appl. Sci. Manuf. 88, 253–262. https://doi.org/10.1016/j.compositesa:2016.06.003.
López-Gómez, José.P., Alexandri, M., Schneider, R., Latorre-Sánchez, M., Coll Lozano, C., Venus, J., 2020a. Organic fraction of municipal solid waste for the production of L-lactic acid with high optical purity. J. Clean. Prod. 247, 119165. https://doi.org/10.1016/j.jclepro.2019.119165.
López-Gómez, J.P., Latorre-Sánchez, M., Unger, P., Schneider, R., Coll Lozano, C., Venus, J., 2019a. Assessing the organic fraction of municipal solid wastes for the production of lactic acid. Biochem. Eng. J. 150, 107251. https://doi.org/10.1016/j.bej.2019.107251.
López-Gómez, J.P., Pérez-Rivero, C., Venus, J., 2020b. Valorisation of solid biowastes: The lactic acid alternative. Process Biochem. 99, 222–235. https://doi.org/10.1016/j.procbio.2020.08.029.
López-Gómez, José.P., Alexandri, M., Schneider, R., Venus, J., 2019b. A review on the current developments in continuous lactic acid fermentations and case studies utilising inexpensive raw materials. Process Biochem. 79, 1–10. https://doi.org/10.1016/j.procbio.2018.12.012.
López-Gómez, José.P., Unger, P., Schneider, R., Venus, J., 2020c. From upstream to purification: production of lactic acid from the organic fraction of municipal solid waste. Waste Biomass Valor. 11 (10), 5247–5254. https://doi.org/10.1007/s12649-020-00992-9.
Mai, T.K., Rodtong, S., Baimark, Y., Rarey, J., Boontawan, A., 2018. Membrane-based purification of optically pure D-lactic acid from fermentation broth to poly(D-lactide) polymer. J. Memb. Sci. 551, 180–190. https://doi.org/10.1016/j.memsci.2018.01.046.
Mandegari, M.A., Farzad, S., van Rensburg, E., Görgens, J.F., 2017. Multi-criteria analysis of a biorefinery for co-production of lactic acid and ethanol from sugarcane lignocellulose. Biofuels. Bioprod. Biorefining. 11 (6), 971–990. https://doi.org/10.1002/bbb.2017.11.issue-610.1002/bbb.1801.
Martinez, F.A.C., Balciunas, E.M., Salgado, J.M., Gonzalez, J.M.D., Converti, A., de Oliveira, R.P.S., 2013. Lactic acid properties, applications and production: A review. Trends Food Sci. Technol. 30, 70–83. https://doi.org/10.1016/j.tifs.2012.11.007.
Mayo, B., Aleksandrzak-Piekarczyk, T., Fernández, M., Kowalczyk, M., Álvarez-Martín, P., Bardowski, J., 2010. Updates in the metabolism of lactic acid bacteria. In: Mozzi, F., Raya, R.R., Vignolo, G.M. (Eds.), Biotechnology of lactic acid bacteria: Novel applications. Blackwell Publishing Ltd, pp. 3–33. https://doi.org/10.1002/9780813820866.ch1.
Michalski, A., Brzezinski, M., Lapienis, G., Biela, T., 2019. Star-shaped and branched polylactides: Synthesis, characterization, and properties. Prog. Polym. Sci. 89, 159–212. https://doi.org/10.1016/j.progpolymsci.2018.10.004.
Murali, N., Srinivas, K., Ahring, B.K., 2017. Biochemical production and separation of carboxylic acids for biorefinery applications. Fermentation. 3 (2), 22. https://doi.org/10.3390/fermentation3020022.
Nduko, J.M., Taguchi, S., 2021. Microbial production of biodegradable lactate-based polymers and oligomeric building blocks from renewable and waste resources. Front. Bioeng. Biotechnol. 8, 1–18. https://doi.org/10.3389/fbioe.2020.618077.
Nielsen, C., Rahman, A., Rehman, A.U., Walsh, M.K., Miller, C.D., 2017. Food waste conversion to microbial polyhydroxyalkanoates. Microb. Biotechnol. 10 (6), 1338–1352. https://doi.org/10.1111/mbt2.2017.10.issue-610.1111/1751-7915.12776.
Ohkouchi, Y., Inoue, Y., 2006. Direct production of l(+)-lactic acid from starch and food wastes using *Lactobacillus manihotivorans* LMG18011. Bioresour. Technol. 97 (13), 1554–1562. https://doi.org/10.1016/j.biortech.2005.06.004.
Olajuyin, A.M., Yang, M., Thygesen, A., Tian, J., Mu, T., Xing, J., 2019. Effective production of succinic acid from coconut water (Cocos nucifera) by metabolically engineered *Escherichia coli* with overexpression of *Bacillus subtilis* pyruvate carboxylase. Biotechnol. Reports 24, e00378. https://doi.org/10.1016/j.btre.2019.e00378.
Ouyang, S., Zou, L., Qiao, H., Shi, J., Zheng, Z., Ouyang, J., 2020. One-pot process for lactic acid production from wheat straw by an adapted *Bacillus coagulans* and identification of genes related to hydrolysate-tolerance. Bioresour. Technol. 315, 123855. https://doi.org/10.1016/j.biortech.2020.123855.
Peinemann, J.C., Demichelis, F., Fiore, S., Pleissner, D., 2019. Techno-economic assessment of non-sterile batch and continuous production of lactic acid from food waste. Bioresour. Technol. 289, 121631. https://doi.org/10.1016/j.biortech.2019.121631.
Peng, K., Koubaa, M., Bals, O., Vorobiev, E., 2020. Recent insights in the impact of emerging technologies on lactic acid bacteria: A review. Food Res. Int. 137, 109544. https://doi.org/10.1016/j.foodres.2020.109544.
Pérez, A.D., Fontalvo, J., 2019. A new concept of liquid membranes in Taylor flow: Performance for lactic acid removal. Chem. Eng. Process. Process Intensif. 139, 95–102. https://doi.org/10.1016/j.cep.2019.03.015.
Pérez, A.D., Van der Bruggen, B., Fontalvo, J., 2019. Modeling of a liquid membrane in Taylor flow integrated with lactic acid fermentation. Chem. Eng. Process. Process Intensif. 144, 107643. https://doi.org/10.1016/j.cep.2019.107643.
Pleissner, D., Demichelis, F., Mariano, S., Fiore, S., Navarro Gutiérrez, I.M., Schneider, R., Venus, J., 2017. Direct production of lactic acid based on simultaneous saccharification and fermentation of mixed restaurant food waste. J. Clean. Prod. 143, 615–623. https://doi.org/10.1016/j.jclepro.2016.12.065.
Pradhan, N., d'Ippolito, G., Dipasquale, L., Esposito, G., Panico, A., Lens, P.N.L., Fontana, A., 2021. Kinetic modeling of hydrogen and L-lactic acid production by *Thermotoga neapolitana* via capnophilic lactic fermentation of starch. Bioresour. Technol. 332, 125127. https://doi.org/10.1016/j.biortech.2021.125127.
Probst, M., Fritschi, A., Wagner, A., Insam, H., 2013. Biowaste: A *Lactobacillus* habitat and lactic acid fermentation substrate. Bioresour. Technol. 143, 647–652. https://doi.org/10.1016/j.biortech.2013.06.022.
Probst, M., Walde, J., Pümpel, T., Wagner, A.O., Insam, H., 2015. A closed loop for municipal organic solid waste by lactic acid fermentation. Bioresour. Technol. 175, 142–151. https://doi.org/10.1016/j.biortech.2014.10.034.
Prückler, M., Lorenz, C., Endo, A., Kraler, M., Dürrschmid, K., Hendriks, K., Soares da Silva, F., Auterith, E., Kneifel, W., Michlmayr, H., 2015. Comparison of homo- and heterofermentative lactic acid bacteria for implementation of fermented wheat bran in bread. Food Microbiol. 49, 211–219.
Rawoof, S.A.A., Kumar, P.S., Vo, D.-V., Devaraj, K., Mani, Y., Devaraj, T., Subramanian, S., 2021. Production of optically pure lactic acid by microbial fermentation: a review. Environ. Chem. Lett. 19 (1), 539–556. https://doi.org/10.1007/s10311-020-01083-w.
Razali, N., Abdullah, A.Z., 2017. Production of lactic acid from glycerol via chemical conversion using solid catalyst: A review. Appl. Catal. A Gen. 543, 234–246. https://doi.org/10.1016/j.apcata.2017.07.002.
Riaz, S., Fatima, N., Rasheed, A., Riaz, M., Anwar, F., Khatoon, Y., 2018. Metabolic engineered biocatalyst: A solution for PLA based problems. Int. J. Biomater. 2018, 1–9. https://doi.org/10.1155/2018/1963024.
Rodrigues, A.C., Haven, M.Ø., Lindedam, J., Felby, C., Gama, M., 2015. Celluclast and Cellic(®) CTec2: Saccharification/fermentation of wheat straw, solid-liquid partition and potential of enzyme recycling by alkaline washing. Enzyme Microb. Technol. 79–80, 70–77. https://doi.org/10.1016/j.enzmictec.2015.06.019.
Romano, A.H., Conway, T., 1996. Evolution of carbohydrate metabolic pathways. Res. Microbiol. 147 (6-7), 448–455.
SAKAI, K., MURATA, Y., YAMAZUMI, H., TAU, Y., MORI, M., MORIGUCHI, M., SHIRAI, Y., 2000. Selective proliferation of lactic acid bacteria and accumulation of lactic acid during open fermentation of kitchen refuse with intermittent pH adjustment. Food Sci. Technol. Res. 6 (2), 140–145. https://doi.org/10.3136/fstr.6.140.
Sankaran, R., Parra Cruz, R.A., Pakalapati, H., Show, P.L., Ling, T.C., Chen, W.-H., Tao, Y., 2020. Recent advances in the pretreatment of microalgal and lignocellulosic biomass: A comprehensive review. Bioresour. Technol. 298, 122476. https://doi.org/10.1016/j.biortech.2019.122476.
Thi, N.B.D., Lin, C.Y., Kumar, G., 2016. Waste-to-wealth for valorization of food waste to hydrogen and methane towards creating a sustainable ideal source of bioenergy. J. Clean. Prod. 122, 29–41. https://doi.org/10.1016/j.jclepro.2016.02.034.
Thomsen, M.H., Thygesen, A., Thomsen, A.B., 2008. Hydrothermal treatment of wheat straw at pilot plant scale using a three-step reactor system aiming at high hemicellulose recovery, high cellulose digestibility and low lignin hydrolysis. Bioresour. Technol. 99 (10), 4221–4228. https://doi.org/10.1016/j.biortech.2007.08.054.
Thomsen, M.H., Thygesen, A., Thomsen, A.B., 2009. Identification and characterization of fermentation inhibitors formed during hydrothermal treatment and following SSF of wheat straw. Appl. Microbiol. Biotechnol. 83 (3), 447–455. https://doi.org/10.1007/s00253-009-1867-1.
Thygesen, A., Ami, J., Fernando, D., Bentil, J., Daniel, G., Mensah, M., Meyer, A.S., 2020. Microstructural and carbohydrate compositional changes induced by enzymatic saccharification of green seaweed from West Africa. Algal Res. 47, 101894. https://doi.org/10.1016/j.algal.2020.101894.
Toldrá, F., Aristoy, M.-C., Mora, L., Reig, M., 2012. Innovations in value-addition of edible meat by-products. Meat Sci. 92 (3), 290–296. https://doi.org/10.1016/j.meatsci.2012.04.004.
Tran, Q.N.M., Mimoto, H., Koyama, M., Nakasaki, K., 2019. Lactic acid bacteria modulate organic acid production during early stages of food waste composting. Sci. Total Environ. 687, 341–347. https://doi.org/10.1016/j.scitotenv.2019.06.113.

Tsapekos, P., Alvarado-Morales, M., Baladi, S., Bosma, E.F., Angelidaki, I., 2020. Fermentative production of lactic acid as a sustainable approach to valorize household bio-waste. Front. Sustain. 1, 1–12. https://doi.org/10.3389/frsus.2020.00004.

Van Breugel, J., Van Krieken, J., Cerdà Baró, A., Vidal Lancis, J.M., Camprubi V.M. 2000. Method of industrial-scale purification of lactic acid.

Van Gansbeghe, F., Bogaert, J.-C., Malhaize, E., Van Gansberghe, M., Wolff, F. 2002. Method for purifying lactic acid.

Wang, J., Gao, M., Wang, Q., Zhang, W., Shirai, Y., 2016. Pilot-scale open fermentation of food waste to produce lactic acid without inoculum addition. RSC Adv. 6 (106), 104354–104358. https://doi.org/10.1039/C6RA22760K.

Wang, X.Q., Wang, Q.H., Zhi Ma, H., Yin, W., 2009. Lactic acid fermentation of food waste using integrated glucoamylase production. J. Chem. Technol. Biotechnol. 84 (1), 139–143. https://doi.org/10.1002/jctb.v84:110.1002/jctb.2007.

Wu, J., Kim, K.H., Jeong, K., Kim, D., Kim, C.S., Ha, J.-M., Chandra, R.P., Saddler, J.N., 2021. The production of lactic acid from chemi-thermomechanical pulps using a chemo-catalytic approach. Bioresour. Technol. 324, 124664. https://doi.org/10.1016/j.biortech.2021.124664.

Yadav, N., Nain, L., Khare, S.K., 2021. One-pot production of lactic acid from rice straw pretreated with ionic liquid. Bioresour. Technol. 323, 124563. https://doi.org/10.1016/j.biortech.2020.124563.

Yang, X., Zhu, M., Huang, X., Lin, C.S.K., Wang, J., Li, S., 2015. Valorisation of mixed bakery waste in non-sterilized fermentation for l-lactic acid production by an evolved *Thermoanaerobacterium* sp. strain. Bioresour. Technol. 198, 47–54. https://doi.org/10.1016/j.biortech.2015.08.108.

Yildirim, I., Weber, C., Schubert, U.S., 2018. Old meets new: Combination of PLA and RDRP to obtain sophisticated macromolecular architectures. Prog. Polym. Sci. 76, 111–150. https://doi.org/10.1016/j.progpolymsci.2017.07.010.

Yin, J., Yu, X., Zhang, Y., Shen, D., Wang, M., Long, Y., Chen, T., 2016. Enhancement of acidogenic fermentation for volatile fatty acid production from food waste: Effect of redox potential and inoculum. Bioresour. Technol. 216, 996–1003. https://doi.org/10.1016/j.biortech.2016.06.053.

Yousuf, A., Bastidas-Oyanedel, J.R., Schmidt, J.E., 2018. Effect of total solid content and pretreatment on the production of lactic acid from mixed culture dark fermentation of food waste. Waste Manag. 77, 516–521. https://doi.org/10.1016/j.wasman.2018.04.035.

Zhang, Z., Tsapekos, P., Alvarado-Morales, M., Angelidaki, I., 2021a. Impact of storage duration and micro-aerobic conditions on lactic acid production from food waste. Bioresour. Technol. 323, 124618. https://doi.org/10.1016/j.biortech.2020.124618.

Zhang, Z., Tsapekos, P., Alvarado-Morales, M., Angelidaki, I., 2021b. Bio-augmentation to improve lactic acid production from source-sorted organic household waste. J. Clean. Prod. 279, 123714. https://doi.org/10.1016/j.jclepro.2020.123714.