Bioresource Technology 215 (2016) 50–62

Contents lists available at ScienceDirect

Bioresource Technology

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

Review

Biorefinery approach for cassava-based industrial wastes: Current status and opportunities

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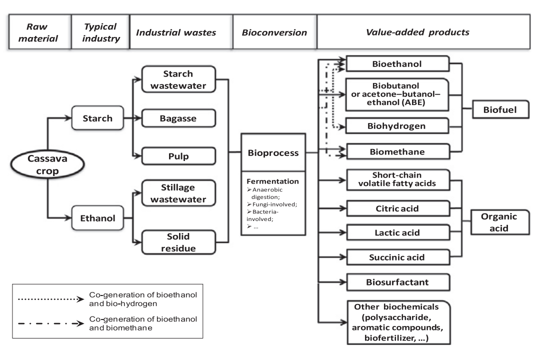
HIGHLIGHTS

- Cassava industrial wastes/residues are rich in organic matters and suspended solids.
- Cassava industrial wastes provide excellent platform to adopt biorefinery approach.
- Bioconversion processes to produce various high-value products are discussed.
- Feasibility of various bioconversion approaches and products is analyzed.
- Propose a biorefinery concept for sustainable development of cassava industries.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 February 2016
Received in revised form 5 April 2016
Accepted 6 April 2016
Available online 8 April 2016

Keywords:
Cassava wastes/residues
Bioconversion
Biorefinery
Bioenergy
Value-added products

ABSTRACT

Cassava, an important food crop, has been extensively employed as raw materials for various agri-industries to produce starch, bioethanol and other biobased products/chemicals. These cassava-based industries also generate large quantities of wastes/residues, rich in organic matter and suspended solids, and pose significant environmental issues. Their complex biochemical composition with high organic content endows them with a great potential for bioconversion into value-added products via biorefinery thereby providing economic and environmental sustainability to cassava industries. This state-of-the-art review covers the source, composition and characteristics of cassava industrial wastes and residues, and their bioconversion into value-added products, mainly biofuels (ethanol and butanol), biogas, biosurfactant, organic acids and other valuable biochemicals among others. This paper also outlines future perspectives with respect to developing more effective and efficient bioconversion processes for converting the cassava wastes and residues into high-value products.

Contents

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http://dx.doi.org/10.1016/j.biortech.2016.04.026
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1. Introduction

Significant increases in the use of renewable resources are urgently required to meet the needs of a growing population and to build a more sustainable society. Agri-industry wastes and residues generated in crop production and food processing are examples of renewable resources. In 2011, a study by the Food and Agriculture Organization (FAO) estimated that approximately one-third of all food produced for human consumption worldwide is discarded, representing about 1.3 billion metric tons of wastes per year (Gustavsson and Stage, 2011). These highly putrescible wastes also cause serious environmental concerns. Organic wastes are readily available and relatively low-cost renewable bioresources for the production of various value-added products (Kreuger et al., 2011). One such waste stream originates from cassava production and processing industries. The wastes/residues from cassava-based industries have enormous potential to generate diverse higher-value products by adopting a biorefinery concept, which could mitigate the need to expand land use for dedicated bioenergy crops, while simultaneously helping to reduce potential food insecurity issues (Pandey et al., 2000).

Cassava (*Manihot esculenta* spp. *esculenta*), a shrubby perennial crop belonging to the family *Euphorbiaceae*, is known as tapioca in Asian countries. This root crop has a high starch content of up to 90% (dry weight). It grows well on infertile land with minimal input of chemicals, such as fertilizers, herbicides and insecticides; making it one of the cheapest and most sustainable agri-based feedstocks. Primarily grown in a tropical climate, more than 70% of cassava production occurs in sub-tropical and tropical regions, between 30°N and 30°S. It is mainly cultivated by small-scale farmers in Africa, Latin America, and Asia, with a total farming area of over 18 million hectares. Africa, the Americas, and Asia have been the top three regions for cassava production between 2000 and 2014 with Asia showing significant growth as shown in Table 1 (FAOSTAT, 2014).

Cassava ranks fourth after rice, sugarcane, and maize, as a cheap source of dietary carbohydrate energy (720×10^{12} kJ/day) and fifth among starch crops in global production. As the world's third largest source of carbohydrates for human consumption, about 60% of the cassava produced worldwide is consumed either as flour or in fermented products such as *gari* and *fufu*. Another large consumer of cassava is the animal feed industries, which use nearly 33% of the world's production. The remaining 7% is used by textile, paper, food, and fermentation industries, among others. Subsequently, a large quantity of highly biodegradable wastes/residues is generated by different cassava-based industries which poses a heavy burden on our environment. Due to the low cost and abundant availability, cassava has become one of the most important sources of starch for bioethanol and other biobased chemicals production in tropical and sub-tropical regions.

The cassava-based wastes/residues can be biologically converted into various high-value products to maximize the effective utilization of this important bioresource. Pandey et al. (2000) summarized the biotechnological developments (predominantly solid-state fermentation) for the utilization of cassava bagasse. Soccol and Vandenberghe (2003) reviewed bioconversion of cassava bagasse into protein, biomolecules, organic acids, food aroma compounds, mushrooms, pigments, etc. in Brazil. Okudoh et al. (2014) examined the anaerobic digestion (biogas) potential of cassava crops and residues, and compared various pretreatment

Table 1
Cassava production by continent and country ($\times 10^7$ metric tons of raw corp) (average in 2000, 2007, and 2014) ("FAOSTAT", 2014).

Year	World	By continent				By country						
		Africa	Americas	Asia	Oceania	Nigeria	Brazil	Thailand	Indonesia	Democratic Republic of the Congo	India	China (Hong Kong, Macao and Taiwan included)
2000	17.61	9.54	3.11	4.95	0.02	3.20	2.33	1.91	1.61	1.60	0.60	0.38
2007	22.78	11.83	3.67	7.26	0.02	4.34	2.65	2.69	2.00	1.50	0.82	0.44
2014	27.03	14.70	3.28	9.04	0.03	5.48	2.32	3.00	2.34	1.66	0.81	0.47

techniques. The authors reported that cassava could potentially become a greatly important energy crop for biogas production in Africa, especially in South Africa.

This review covers the composition, source and characteristics of cassava industrial wastes and residues, and their bioconversion into value-added products, mainly biofuels (ethanol and butanol), biogas, biosurfactant, organic acids and other valuable biochemicals among others. This paper also outlines the future perspectives with respect to developing more effective and efficient bioconversion processes for converting the cassava wastes and residues into higher value products.

2. Generation of cassava-based industrial wastes

While most of the cassava produced in Africa is used for food, other regions such as Asia have been promoting the development of the crop for various agri-industries and renewable energy production, especially bioethanol. The first wave of cassava processing technology in South Asia is for the feed and flour production. The rapidly increasing demand for cassava flour is driving the starch processing industry toward larger-scale production methods. Most of the cassava starch is further processed to generate a range of modified starches for incorporation in various food products, as well as for use as a feedstock for manufacture of sweeteners, fructose, alcohol and monosodium glutamate. On the other hand, cassava has also been used for bioethanol production, and is widely employed in fuel ethanol production. The critical steps for cassava-to-ethanol conversion are the initial enzymatic liberation of sugars and the subsequent fermentation of these resulting sugars by yeast. Taking China as an instance, there are more than 30 cassava-based alcohol enterprises at present, with the total ethanol production of more than 400,000 metric tons annually. By 2020, an increase of cassava-based ethanol production is expected to be one million metric tons, with which an excessive fresh cassava demand of 7 million metric tons will consequently accompany. As a result of this widespread growth of cassava-based industries, large quantities of wastes and residues will be generated (Patle and Lal, 2008). The following section covers the generation of wastes/residues and their bioconversion into value-added products using advanced biorefinery concepts.

2.1. Cassava starch industrial wastes

Cassava wastes/residues are generated during the separation of flour and starch from cassava. This involves several steps: peeling and washing, grating, pressing, disintegration, sifting, drying, milling, and screening. In general, there are four categories of waste/residue streams: peels from initial processing, fibrous by-products from crushing and sieving, starch residues after starch settling, and wastewater effluents (Ubalua, 2007). The solid waste/residue from cassava starch and flour processing is termed as bagasse, pulp or thippi (Pandey et al., 2000; Patle and Lal, 2008; Sriroth et al., 2000), while the processing wastewater is called *manipueira* in Brazil (Nitschke and Pastore, 2006). The processing of fresh raw materials gives rise to between 8.85 and 10.62 metric tons of liquid waste per metric ton of cassava processed, containing approximately 1% total solids (TS). In addition, between 0.93 and 1.12 metric tons of wet cassava bagasse and peels are produced per metric ton of dry cassava processed. In Thailand, an average of 5.15 million metric tons of cassava pulp wastes/residues is derived annually from cassava starch industries (Ghimire et al., 2015). Those cassava solid wastes/residues comprise of root skin, fibrous residues, and black starch. Black starch (~2.5% of root weight) is a by-product consisting of starch and other non-soluble organic substances of low value which can then be broken down into simple sugars by either acid treatment or enzymatic treatment (Patle and Lal, 2008).

Cassava bagasse, a typical solid residue of cassava processing contains between 40.1% and 75.1% starch (dry weight) and between 14.9% and 50.6% fiber, which is mainly composed of cellulose, and other non-starch polysaccharides (Table 2). As for the cassava starch wastewater, this acidic or weakly acidic liquid is rich in total carbohydrate (9.6–37.5 g/L) and nutrients (N and P contents can be as high as 1300 and 780 mg/L, respectively (Table 2)). So it may serve as an ideal feedstock for dark fermentation to produce hydrogen and volatile fatty acids (VFAs). Considering the poor protein content of cassava bagasse, it is unattractive as an animal feed. A persisting problem is that cassava solid wastes/residues differ in their composition, possibly because using different parts of cassava leads to variation in waste compositions, and processing takes place under poorly controlled environmental conditions (Pandey et al., 2000). Wastes are usually stored in an open field. They spoil rapidly, not only causing environmental problems including contamination of water bodies, but also emanating strong and offensive odors (Li and Zhu, 2011).

2.2. Cassava ethanol industrial wastes

Cassava is an attractive feedstock for fuel ethanol production given its low cost, availability and non-competition with direct

Table 2
Physio-chemical characteristics of cassava starch wastes (wastewater and solid wastes).

Parameters	Wastewater [a]	Parameters (%, by dry weight)	Bagasse [b]
Total solids (g/L)	4.5–38.2	Starch	40.1–75.1
Volatile solids (g/L)	3.4–33.0	Crude fiber	14.9–50.6
Total chemical oxygen demand (g/L)	8.0–66.2	Cellulose	4.1–11.4
Soluble chemical oxygen demand (g/L)	14.2–34.5	Hemicellulose	4.2–8.3
Biochemical oxygen demand (g/L)	–	Lignin	1.2
Total carbohydrate (g/L)	9.6–37.5	Total ash	0.7–11.9
Solid carbohydrate (g/L)	–	Crude fat (lipids)	0.5–1.1
Dissolved sugar (g/L)	–	Crude protein	0.3–1.6
Oil and grease (g/L)	0.6	Total solids	–
Total protein (g/L)	2.3	Volatile solids	–
Total nitrogen (g/L)	0.1–1.3	Total nitrogen	–
NH_3–N (mg/L)	–		
Total phosphorous (mg/L)	70.0–780.0		
pH	3.6–6.2		

Note: –: data not available.
References:
[a] Amorim et al. (2014), Auphimai et al. (2014), O-Thong et al. (2011), Sreethawong et al. (2010).
[b] Leano and Babel (2012), Li and Zhu (2011), Pandey et al. (2000), Ray et al. (2008).

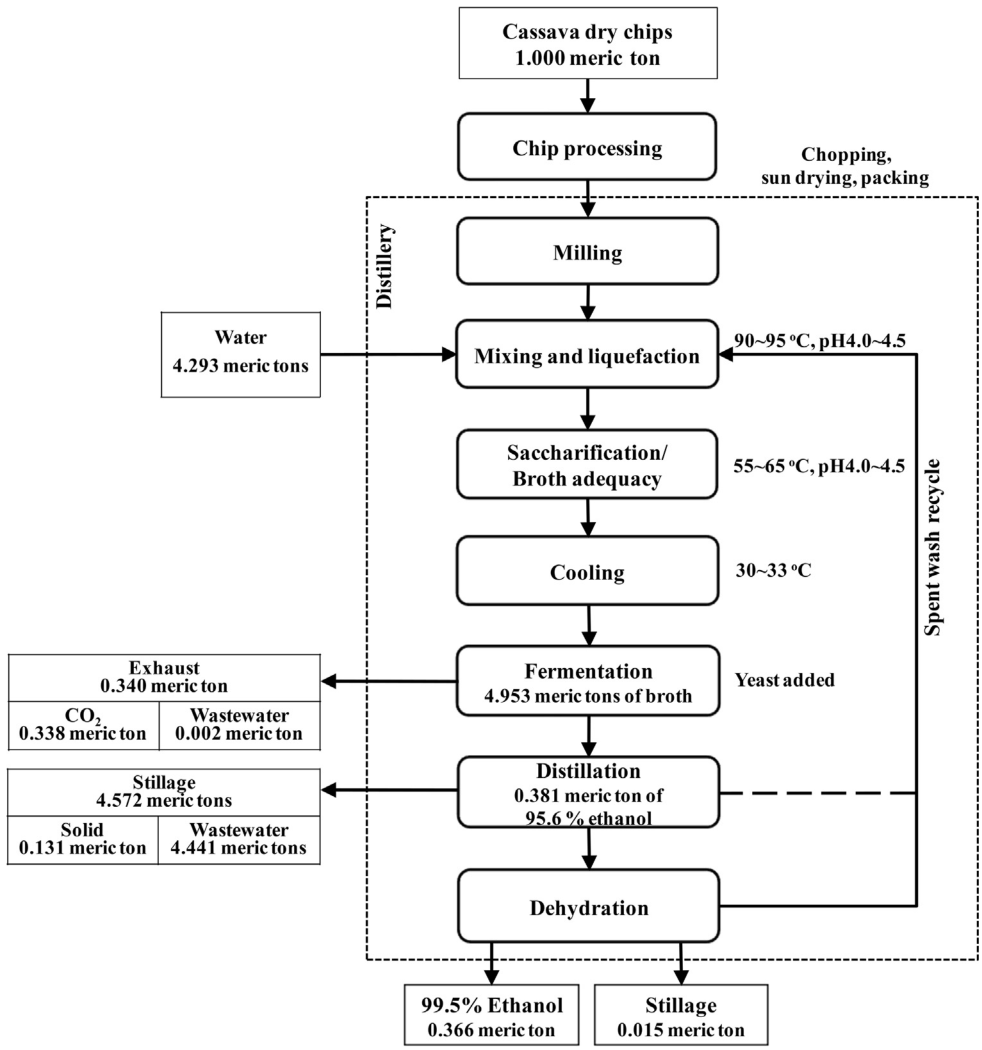

Fig. 1. Schematic diagram of cassava-based ethanol production process with mass balance.

food/feed supplies. The cassava-to-ethanol conversion process has been well established in China, Thailand, and Saharan Africa. Fig. 1 describes the bioethanol production from cassava chips; the waste generation and mass balance during process are given as well (Leng et al., 2008). Following liquefaction, saccharification, and fermentation, the ethanol is separated through distillation, leaving large quantities of cassava stillage (i.e., cassava ethanol wastewater, distillery slops, or vinasse) as a waste product. The cassava-to-ethanol conversion process is also an intensively water consuming process, giving rise to approximately 8–12 metric tons of cassava stillage per metric ton of ethanol produced.

This cassava stillage is an acidic liquid waste with high levels of organic pollutants and suspended solids. Characteristics of cassava stillage from different ethanol plants are summarized in Table 3. The pH of cassava stillage ranges from 3.8 to 4.2. The TS, total chemical oxygen demand (COD), and total carbohydrate are 80.0 g/L, 140.0 g/L and 45.2 g/L, respectively, almost over 2-folds greater than that in the cassava starch wastewater (Table 2). The COD:N:P ratio is nearly 200:5:1, which is suitable for bioconversion to methane via anaerobic digestion. It should be noted that, besides the soluble fraction of total COD (TCOD), the remaining part (around 50% of the TCOD) is from the organic particulate components (Luo et al., 2009). Those solids in cassava stillage are difficult to separately recover due to the high viscosity and the low nutrient content.

Compared with the cassava bagasse from starch processing, solid wastes and residues of cassava stillage are rather high in lignocellulose content, composed of cellulose, hemicellulose and lignin (Table 3). The cellulose, accounting for approximately 25% of the dry cassava stillage residue, consists of both crystalline and amorphous structures, and the microfibril bundles of the cellulose are bound through relatively weak hydrogen bonds. Lignin, approximately 17.8% (dry weight), gives the cassava stillage residue resistance against microbial attack. The hemicellulose (approximately 12.3% (dry weight)) serves as a connection between the cellulose fibers and lignin, and gives more rigidity to the whole cellulose-hemicellulose-lignin network. The high lignocellulose but poor protein content of cassava stillage limit its utilization as an animal feed (Luo et al., 2009; Pandey et al., 2000). Nevertheless, this abundance and low cost endows cassava stillage as a good source for the fermentative production of biofuels and biochemicals.

3. Bioconversion of cassava-based industrial wastes

Cassava-based industrial residues contain high concentrations of organics (mainly carbohydrate) and ash as discussed earlier. Its dark color hinders photosynthesis by blocking sunlight and is thus deleterious to aquatic life. If disposed off untreated, it raises

Table 3
Physio-chemical characteristics of cassava ethanol residues.

Parameters	Stillage [a]	Parameters (%, by dry weight)	Solid residues [b]
Total solids (g/L)	0.019–80.0	Starch	–
Volatile solids (g/L)	0.014–65.0	Crude fiber	–
Total chemical oxygen demand (g/L)	14.5–140.0	Cellulose	24.5–25.3
Soluble chemical oxygen demand (g/L)	20.0–45.0	Hemicellulose	17.5–18.1
Biochemical oxygen demand (g/L)	24.0–35.0	Lignin	12.1–12.5
Total carbohydrate (g/L)	5.3–45.2	Total ash	–
Solid carbohydrate (g/L)	4.6–8.3	Crude fat (lipids)	4.5–4.7
Dissolved sugar (g/L)	4.3–4.8	Crude protein	–
Oil and grease (g/L)	–	Total solids	94.2–97.0
Total protein (g/L)	0.9–5.7	Volatile solids	83.0–85.6
Total nitrogen (g/L)	0.2–1.4	Total nitrogen	1.3–1.5
NH_3–N (mg/L)	127.0–275.0		
Total phosphorous (mg/L)	70.0–960.0		
pH	3.8–4.2		

Note: –: data not available.
References:
[a] Fuess and Garcia (2015), Intanoo et al. (2014), Luo et al. (2010a, 2010b, 2010c, 2010d),Wang et al. (2011, 2012, 2013), Zhang et al. (2013).
[b] Zhang et al. (2011b, 2013).

serious environmental concerns, which may negatively impact the sustainability of these industries. To achieve sustainability, these carbohydrate-rich wastes should be further exploited for the production of additional useful products and for the creation of employment and additional revenue. Hence, a reasonable utilization of the cassava residues for upgrading the cassava fuel ethanol value has become critically important for their long-term sustainability. There is growing interest in the bioconversion and biorefinery of cassava-based wastes/residues into different fuels and bio-based products due to important issues related to not only environmental concerns but also energy, and social considerations.

Fig. 2 presents a proposed cassava-based industrial process based on the bioconversion of these wastes. The development of bioprocesses for economically utilizing those cassava industrial wastes for value-added products (i.e., biofuels, biochemicals and other biobased products) would serve the agri- and industrial processing sectors by making them more resource efficient and sustainable, which is essential for their competitiveness. A great effort has been dedicated toward production of a wide variety of bioproducts (for instance, biofuels, organic acids, biochemicals) and attainment of net energy producer by making full use of the different components of cassava wastes/residues.

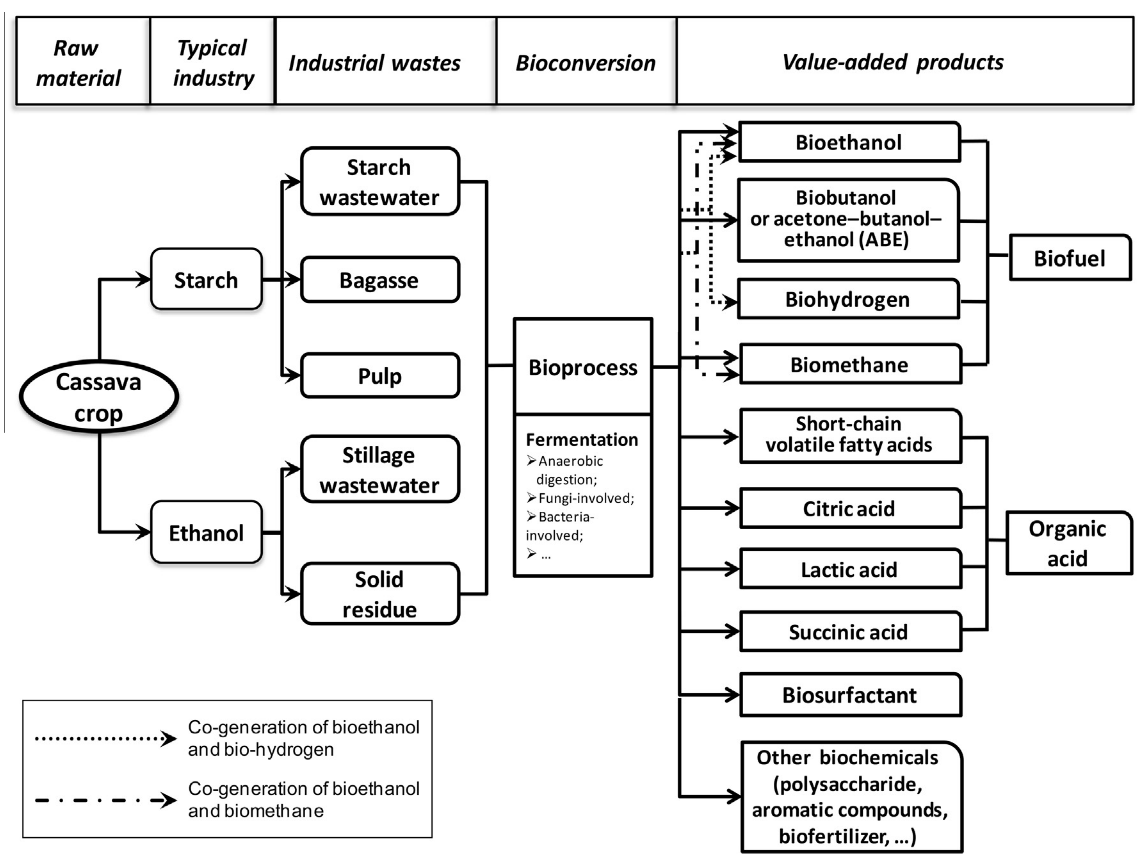

Fig. 2. Schematic diagram of cassava-based industrial processes and the bioconversion of cassava industrial wastes into value-added products.

3.1. Biofuels

3.1.1. Bioethanol and acetone-butanol-ethanol (ABE)

Lignocellulosic materials are the most widely available low-cost renewable resources in the world to be considered for ethanol production. This suggests the great potential of cassava industrial wastes for generating ethanol since the lignocellulosic fiber removed from cassava pulp may be an ideal substrate. Using Nigeria as an example, the potential for cellulosic ethanol production is 7.56 million cubic meters per year, exceeding the local governmental mandate of 10% renewable fuel and creating a need for processing facilities devoted to the utilization of a single feedstock (Iye and Bilsborrow, 2013).

Several attempts have been made to obtain a high ethanol yield from cassava industrial wastes by hydrolysis and fermentation of carbohydrate. Typically, using the cassava pulp as substrate for yeast fermentation, the ethanol production of 0.30–0.51 g ethanol/g substrate could be achieved. Hydrothermal treatment of the inexpensive cassava residue was confirmed to gain high yields of glucose for ethanol production (Nair et al., 2011). The most cost-intensive processes in cassava ethanol production are the hydrolysis process to obtain the fermentable sugars (i.e., glucose). This hydrolysis can be catalyzed by acids, either concentrated or dilute, or by enzymes. To overcome the energy intensive drawbacks of acid hydrolysis, enzymatic treatment using amylase has been optimized for the hydrolysis of thippi. Good ethanol yields could be obtained with a mixture of *Candida tropicalis* and *Zymomonas mobilis* during thippi hydrolysate fermentation. *C. tropicalis* produces a starch-decomposing enzyme and carries out complete fermentation of thippi while hydrolyzing the substrate (Patle and Lal, 2008). A multi-activity enzyme from *Aspergillus niger* BCC17849, used in an alternative cassava pulp saccharification process, obviates the need for a pre-gelatinization step. Compared to the conventional enzymatic process, this non-thermal enzymatic saccharification process was more energetically efficient and resulted in higher fermentable sugar yields (Rattanachomsri et al., 2009). Other pretreatment methods have also been evaluated to optimize the performance of cassava wastes to ethanol process. Through wet oxidation, the cellulose content in the solid fraction of cassava residues increased from 361 to 600 g/kg, and the enzyme hydrolysis of cellulose was enhanced (Martin and Thomsen, 2007). Ultrasound was also tested for its ability to promote enzymatic hydrolysis of cassava waste using α-amylase and amyloglucosidase to obtain fermentable sugars (Leaes et al., 2013). The best yield of total reducing sugar released that was achieved with ultrasound was 116.1 g/L compared to 83.1 g/L without ultrasound pretreatment.

As aforementioned, cassava industrial wastes have a high proportion of structural carbohydrate and lignin, and the hydrolysis of these components is the first step for either fermentation to ethanol or anaerobic digestion to biogas. Therefore, novel integrated fermentation processes for obtaining biofuels (bioethanol, biomethane and/or biohydrogen) from cassava wastes have been explored. In the study of Zhang et al. (2010), the waste stillage obtained from ethanol distillation was treated by anaerobic digestion and then recycled for substrate preparation in the subsequent ethanol fermentation run. With two series-connected tanks, ethanol fermentation was significantly improved and the fermentation lag time was completely eliminated, resulting from the reduction in organic acid concentrations. Following this work, the anaerobic digester effluent was further found to be a good nitrogen source for ethanol fermentation, giving rise to higher ethanol production rates (Wang et al., 2012). Thereafter, Wang et al. (2014) mixed thin stillage (the supernatant of stillage after centrifugation) with the anaerobic digestion effluent, which was then used as feedstock for ethanol fermentation. With this method, the average ethanol production was enhanced to 13.55% (v/v) (around 0.17% higher than that in the first batch without the mixture of thin stillage and digestate), and the methane yield of 303 L/kg COD removed was maintained. In order to enhance the enzymatic hydrolysis of lignocelluloses, alkali exposure followed by enzymatic digestion was investigated to treat cassava wastes. A bioethanol volumetric productivity of 1.3 g/(L h), was attained, which was higher than the 0.5 g/(L h) obtained from peels pretreated with enzymes alone; a 56% increase in methane yield was also achieved (Moshi et al., 2015). As for the production of ethanol accompanied by hydrogen from cassava pulp, the co-culture of *Clostridium thermocellum* and *Thermoanaerobacterium aotearoense* in a biphasic fermentation provided a consolidated bioprocessing for greater production. With appropriate conditions, the ethanol level reached 8.83 ± 0.31 g/L with a fermentation efficiency of 65%. The hydrogen production by the co-culture system was 1.5 and 2.1-fold higher than that

Table 4
Biomethane production of cassava-based industrial wastes.

Substrate	Reactor	Temperature (°C)	Pretreatment	Performance		Reference
				COD removal (%)	Methane yield (mL CH_4/g VS)	
Cassava starch wastewater	Hybrid reactor	25	–	~93.0	14.4 [a]	Paixao et al. (2000)
Cassava starch wastewater	Batch reactor	37	–	–	271.0–290.0 [b]	Auphimai et al. (2014)
Cassava stillage	ASBR	~55	–	~85.1	200.0–230.0 [b]	Luo et al. (2009)
Cassava stillage	Batch reactor	~55	Pre-hydrolyzing substrates	–	259.5	Zhang et al. (2011a)
Cassava stillage	Batch reactor	~55	Thermal-dilute sulfuric acid	–	248.0	Zhang et al. (2011b)
Cassava stillage	ASBR	~55	Pre-hydrolyzing substrates	~80.0	147.0 [c]	Zhang et al. (2013)
Cassava pulp co-digested with pig manure	Semi-CSTR	37	–	~57.0	306.0	Panichnumsin et al. (2010)
Cassava dregs co-digested with pig manure	SBR-CSTR	~25, 37	–	~69.2	352.0	Ren et al. (2014)

Note: –: data not available.
[a] L/d.
[b] mL CH_4/g COD_{added}.
[c] mL CH_4/g $COD_{removed}$.

produced by mono-cultures of *C. thermocellum* and *T. aotearoense*, respectively (Li and Zhu, 2011).

Biobutanol is another attractive alcohol for vehicle as a transportation fuel due to its higher octane number, greater energy content, lower volatility, and similar air-to-fuel ratio to gasoline, as compared with ethanol. It can not only be flexibly mixed with gasoline in varied ratios, but it can also be safely stored. Biological production of butanol has a long history as an industrially significant fermentation process. Starchy lignocellulosic biomass from cassava pulp and tapioca starch wastewater is a promising substrate for ABE fermentation. The cassava bagasse hydrolysate was used for the production of n-butanol in ABE fermentation with continuous gas stripping. A super-butanol-producing strain JB200 utilized the highly concentrated cassava bagasse hydrolysate containing mainly glucose and produced 108.5 g/L ABE in fed-batch fermentation, with simultaneous butanol recovery by gas stripping. With periodical nutrient supplementations, the integrated fermentation process maintained a stable productivity and high butanol yield for an extended period, making the process attractive for industrial production (Lu et al., 2012). It should also be noted that pretreatment is a key determinant of the yields and manufacturing costs in ABE/ethanol fermentations. A recently developed one step enzymatic pretreatment method may improve ABE/ethanol yields and reduce the production costs by shortening the fermentation time, lowering the required amount of enzyme, and improving the enzymatic hydrolysis.

3.1.2. Biomethane

Anaerobic digestion (AD) has been well developed and commercialized for the stabilization of various organic waste streams over the past few decades. It has been applied in most cassava-based industries for the biogas production from cassava stillage or starch residues, demonstrating to be effective and economical (Paixao et al., 2000). In AD, organic compounds are converted into renewable energy in the form of methane gas. Most studies reported on biomethane production from cassava industrial wastes originated from China, Thailand and Colombia and a few African countries such as Nigeria, Tanzania and Kenya. Table 4 shows representative batch or continuous AD processes under either thermophilic or mesophilic conditions. As aforementioned, the high organic loading but low suspended solids content (1–4%) seriously limits the direct application of cassava wastes in the efficient upflow anaerobic sludge blanket (UASB) or expanded granular sludge bed systems. Thus, continuous-stirred tank reactor (CSTR) is often the most widely used digester type in cassava plants. Normally, CSTR is employed in the first stage of anaerobic digestion, followed by UASB as the secondary stage for cassava stillage treatment in China. Since the major solid component in cassava stillage is lignocellulose, the development of anaerobic biotechnology capable of digesting the cassava industrial wastes has been continuously pursued by researchers. Luo et al. (2009) reported that anaerobic sequencing batch reactor (ASBR) could efficiently digest cassava stillage at a hydraulic retention time of 5 days and an organic loading rate of 11.3 kg COD/(m^3 d). The stability of digested cassava stillage was significantly improved.

Hydrolysis or solubilization of solids is a rate-limiting step of cassava stillage digestion for biogas production. The complex lignocellulosic structure makes the digestion of cassava residues difficult to hydrolyze and consequently reduces the methane yield. Strategies must be applied to enhance the digestibility of cassava stillage prior to anaerobic digestion. The anaerobic digestion with two physically separated stages (e.g., acidogenic and methanogenic)

Table 5
Hydrogen and hydrogen-methane co-generation from cassava-based industrial wastes.

Substrate	Reactor	Temperature (°C)	Pretreatment	Yield		Reference
				Hydrogen	Methane	
Cassava starch wastewater	ASBR	37	–	438 mL H_2/g $COD_{removed}$	–	Sreethawong et al. (2010)
	CSTR	60	–	124.9–287 mL H_2/g starch	–	O-Thong et al. (2011)
	Batch reactor	36	–	2.41 mol H_2/mol glucose	–	Cappelletti et al. (2011)
	Batch reactor	37	Sonication and enzymatic hydrolysis	5.02 mol H_2/g COD	–	Leano and Babel (2012)
	Anaerobic fluidized bed reactor (AFBR)	~28	–	1.91 mol H_2/mol glucose	–	Amorim et al. (2014)
Cassava stillage	Batch-CSTR	60	Chloroform, base, acid, heat and loading-shock	32.9–65.3 mL H_2/g VS	–	Luo et al. (2010a)
	Batch reactor	60	–	82.9–92.3 mL H_2/g VS	–	Luo et al. (2010b)
	Batch reactor	37, 60, 70	–	53.3–67.8 mL H_2/g VS	–	Luo et al. (2010d)
	Batch reactor	60	Acid and alkaline	56.7–93.9 mL H_2/g VS	–	Wang et al. (2013)
	Two-stage CSTR	55	–	62.7–75.3 mL H_2/g VS	333.6–362.2 mL CH_4/g VS	Luo et al. (2011)
	Two-stage UASB	55	–	54.2 mL H_2/g COD_{added}	164.9 mL CH_4/g COD_{added}	Intanoo et al. (2014)
Cassava residues	Batch reactor	~35	Microwave-heating, steam-heating and enzymatic hydrolysis	102.1–106.2 mL H_2/g VS	75.4–93.2 mL CH_4/g VS	Cheng et al. (2015)
Cassava stillage co-digested with excess sludge	Semi CSTRs	60	–	70.3–77.7 mL H_2/g VS	366.6–392.6 mL CH_4/g VS	Wang et al. (2011)
Cassava stillage co-digested with excess sludge	Semi-CSTRs	60	Heating cassava excess sludge	34.2–40.0 mL H_2/g VS	354.4–375.4 mL CH_4/g VS	Wang et al. (2012)

Note: –: data not available.

is the one of choices to achieve efficient digestion and stable performance. A CSTR at acidogenic phase and a hybrid reactor at methanogenic phase in a continuous mode were operated for 300 days to digest residues from a flour and cassava meal industry (Paixao et al., 2000). The biogas production with methane content of 80% and COD reduction of 96% was achieved. To enhance the digestion of the cassava residues and distillery wastewater, a biphasic process (hydrolytic reactor-ASBR) was employed in the work of Zhang et al. (2013), where a cellulolytic microbial consortium was initially used to pre-hydrolyze cassava stillage, followed by methane production in an ASBR. The methanogenic phase was more stable and generated higher methane yields with the assistance of a pre-hydrolytic step.

It should be noted that co-digestion of energy crops and crop residues with manure can improve the biogas yield by: (i) helping to maintain an optimal pH for methanogens; (ii) decreasing free ammonia/ammonium inhibition, which may occur in anaerobic digestion of manure alone; and (iii) providing an optimal C/N ratio for efficient digestion. In view of this, co-digestion of cassava wastes with animal manure was recently investigated. The co-digestion of pig manure and cassava dregs was reported to support higher quantity and diversity of methanogens (Ren et al., 2014).

3.1.3. Biohydrogen

It is widely recognized that carbohydrate-rich waste is ideal substrate for the fermentative hydrogen production. Thus, cassava industrial wastes are of interest as a potential substrate for biohydrogen production. For hydrogen generation from cassava stillage, Luo et al. (2010a, 2010b, 2010d) systematically investigated influences of temperature, pH, and other operational conditions upon the fermentative process and hydrogen production efficiency. The performance of a hydrogen production system is likely related to favorable C:N and C:P ratios and to the presence of other intrinsic nutrients. A maximum specific hydrogen production rate and hydrogen yield of 5680 mL H_2/(L d) and 438 mL H_2/g $COD_{removed}$, respectively, were obtained in an ASBR in which the stoichiometric COD:N ratio was 100:2.2. Conversely, the presence of excess nitrogen was likely led to higher concentrations of organic acids and ethanol, which lowered the hydrogen production efficiency (Sreethawong et al., 2010). The fermentative hydrogen production from the cassava starch processing wastes has also been investigated by others. Natural microbial consortia from hot spring samples and pure hydrogen production bacteria (such as *Clostridium acetobutylicum*) were employed to improve the hydrogen yield, respectively. The former could give rise to the maximum hydrogen yield of 287 mL H_2/g starch in the cassava starch processing wastewater (O-Thong et al., 2011), while the latter furnished 2.4 mol H_2/mol glucose with efficiency of glucose conversion into H_2 of 60% (mol/mol) at lower COD concentration of cassava starch wastewater (Cappelletti et al., 2011).

Various pretreatment methods have been applied on either inoculums or substrates to improve hydrogen production from cassava wastes. Wang et al. (2013) found that both acidic and alkaline pretreatment could improve the hydrogen yield, acid enhanced the release of soluble carbohydrate while alkali stimulated soluble total organic carbon (TOC) production from cassava stillage. A maximum hydrogen yield of 93.9 mL/g volatile solids (VS) was achieved. But the pretreatment of the inoculum had no effect on the thermophilic continuous hydrogen production via dark fermentation of cassava stillage (Luo et al., 2010a). The attempts at pretreating the substrate of cassava wastewater with sonication and enzymes were also carried out. Superior results were obtained when the wastewater was pretreated with a-amylase at 0.20% at pH 7.0 with a hydrogen yield of 5.0 mol H_2/g COD and a COD removal of 60% (Leano and Babel, 2012).

3.1.4. Co-digestion of substrates and co-generation of gaseous biofuels

The co-digestion of cassava stillage and recycled excess sludge may increase both the buffering capacity and the substrate utilization. Table 5 depicts the production of biohydrogen and/or

Table 6
Various organic compounds produced from cassava industrial wastes under the mesophilic conditions.

Product	Process	Substrate	Carbon source	Microorganism	Reference
VFAs	Anaerobic acidogenesis	Anaerobic sludge from a paper mill	Cassava thin stillage	Mixed acidogenic bacteria	Xie et al. (2014)
	Anaerobic acidogenesis	Anaerobic sludge from swine manure treatment	Cassava sour starch wastewater	Mixed acidogenic bacteria	Mahmud Hasan et al. (2015)
	Fed-batch fermentation	Customized basal medium	Cassava bagasse hydrolysate	Heterotrophic *Chlorella protothecoides*	Chen et al. (2015)
Citric acid	Solid-state fermentation	Thermally treated cassava bagasse	Cassava bagasse	seven strains of *Aspergillus niger*	Vandenberghe et al. (2000, 2004)
		Thermally treated cassava bagasse	Cassava bagasse	*Aspergillus niger* LPB21	Prado et al. (2004, 2005a)
		Thermally treated and untreated cassava bagasse	Cassava bagasse	*Aspergillus niger* LPB21	Prado et al. (2005b)
Lactic acid	Solid- substrate Fermentation	Cassava fibrous residues	Cassava fibrous residues	*Lactobacillus plantarum* MTCC 1407	Ray et al. (2008)
	Fermentation	Cassava pulp	Cassava pulp hydrolysate	*Rhizopus oryzae* NRRL395	Thongchul et al. (2009)
	Fermentation	Cassava stillage	Glucose	*Lactobacillus paracasei* KCTC 11710BP	Moon et al. (2013)
Succinic acid	Immobilized fermentation system	Cassava bagasse hydrolysate minerals and neutralizer	Cassava bagasse hydrolysate	*Corynebacterium glutamicum* strain 534	Shi et al. (2014)
Aroma compounds	Solid-state fermentation	Cassava bagasse	Cassava bagasse	*Kluyveromyces marxianus* ATCC 10022	Medeiros et al. (2001)
	Fermentation	Cassava medium and mineral medium	Orange essential oil	*Penicillium* sp. 2025, *Aspergillus* sp. 2038,and *Fusarium oxysporum* 152B	Marostica and Pastore (2007)
Biosurfactant	Fermentation	Synthetic mineral medium	*Manipueira*	*Bacillus* sp.	Nitschke et al. (2004)
		Manipueira	*Manipueira*	*Bacillus subtilis* LB5a strain	Nitschke and Pastore (2006), Barros et al. (2008)

biomethane from unique or mixed cassava wastes reported in literature. Wang et al. (2011, 2012) studied thermophilic co-fermentation of cassava stillage and solid wastes (i.e., cassava excess sludge) for anaerobic acidification and subsequent methane production. A 46% increase in hydrogen yield through co-digestion was attained compared with the yield from cassava stillage alone. The co-digestion of cassava industrial residues and other biomass (sludge and animal manure) improved the biogas yield from 248–260 mL CH_4/g VS to 306–365 mL CH_4/g VS, with 15–16 MJ/kg VS energetic potential as calculated by Wang et al. (2011, 2012).

Since dark fermentation usually leads to different mixtures of VFAs, resulting in relatively low hydrogen yields, photo-fermentation by purple non-sulfur bacteria has been integrated to obtain high hydrogen yields from VFAs. To maximize energy recovery from cassava wastewater/waste with minimal operational costs, integrated processes have been explored. Zong et al. (2009) demonstrated that, with cassava and food wastes as the substrate, a two-step process combining dark-fermentation and photo-fermentation greatly improved both biohydrogen production, and the consumption of substrates and volatile fatty acids. Co-generation of hydrogen and methane in a biphasic anaerobic process has also been investigated for additional energy production. Luo et al. (2010c, 2011) successively studied the co-generation of hydrogen and methane from cassava stillage. The system was confirmed to be more stable and efficient than a single-stage process. A recycling strategy was also employed to minimize the use of NaOH for pH control in the two-stage UASB system under thermophilic conditions (Intanoo et al., 2014). Elsewhere, Cheng et al. (2015) found that the microwave-heated acid pretreatment and enzyme hydrolysis of cassava residues led to higher hydrogen yields, lower methane yields, and greater total energy conversion efficiency, compared with the steam-heated acid pretreatment.

3.2. Organic acids

In addition to biofuels, it is noteworthy that the fermentation of cassava-waste based substrates benefits the production of organic compounds (especially acids) resulting in increased bioconversion efficiency and system stability. Table 6 shows different microorganisms cultivated on cassava industrial wastes for various purposes as presented in Sections 3.2–3.4. The synthesis of different types of organic acids (including VFAs, citric acid, lactic acid and succinic acid) via biological process has been attracting increased attention considering their common usage in bioenergy, food, chemical and pharmaceutical industries.

3.2.1. Short-chain volatile fatty acid (SCVFA)

Accompanying biohydrogen production, quantities of SCVFAs (mainly acetic, propionic, butyric and valeric acids) can be obtained as metabolic byproducts. It has been observed that butyrate was the most significant VFA species during the thermophilic biohydrogen production from cassava stillage, accounting for >80% of the total VFA/ethanol (Luo et al., 2010a). Xie et al. (2014) further investigated pH effects on the VFA composition and production from cassava thin stillage using a pH-adjustment strategy. At an initial pH range of 7.0–11.0, a relatively high VFA concentration of about 9 g COD/L was obtained. The specific VFA production (g COD/g initial SCOD) increased from 0.27 to 0.47 to 0.67 at pH 8.0 and from 0.26 to 0.68 to 0.81 at pH 9.0 (initial pH, intermittent pH, and continuous pH adjustment, respectively). The intermittent pH was controlled by adjusting the pH of the system in every 12 h. The dominant VFA species changed significantly with the increasing frequency of the pH adjustment. At an initial pH of 8.0 or 9.0, the dominant VFA was butyrate, followed by acetate and propionate; at a constant pH of 8.0 or 9.0, acetate and propionate were dominant, with only a small percentage of butyrate (5%).

Mahmud Hasan et al. (2015) examined the VFA production from the cassava starch wastewater. The peak VFA production occurred in 45 h (pH 5.9) with a predominance of acetic acid (63%) and butyric acid (22%), followed by propionic acid (12%). Decreases in amounts of cyanide (12.9%) and COD (21.6%) were observed, in addition to the production of biogas (0.53 mL/h). The high yield of reducing sugar in the cassava bagasse hydrolysate suggests that it is a superior carbon source in comparison to glucose. Thus, a fermentation process using cassava bagasse hydrolysate to obtain high yields of fatty acids and neutral lipids from heterotrophic *Chlorella protothecoides* was developed. The intercellular lipid produced in that system was suitable for the synthesis of high-quality biodiesel (Chen et al., 2015).

3.2.2. Citric acid

Citric acid is among the most significant commercial products, with comprehensive applications in food, pharmaceutical and other industries. Almost all citric acid is produced by fermentation, mainly via submerged fermentation of starch- or sucrose-based media by the filamentous fungus *A. niger*. Over the past 15 years, the research groups of Vandenberghe et al. (2000, 2004) and Prado et al. (2005a,b) have focused on the solid-state fermentation of cassava bagasse for citric acid production. The fungal strain, *A. niger* LPB 21 was shown to be well adapted to cassava bagasse as a substrate. Optimization of the solid-state fermentation process parameters, including temperature, pH, initial humidity, aeration, and nutrient composition, was investigated at both laboratory and semi-pilot scales. Thermal treatment with an aeration rate of 60 mL/min (3 mL/(g min)) and a 60% initial humidity resulted in citric production level as high as 265.7 g/kg dry cassava bagasse (Vandenberghe et al., 2004). The advantage of limited biomass production in glass columns was reported. In particular, for semi-pilot scale citric acid production, the same yield was achieved with a tray-type bioreactor as with a horizontal drum, but the tray-type had advantages in terms of costs and energy saving (Prado et al., 2005a,b).

3.2.3. Lactic acid

Lactic acid is extensively used in the manufacture of emulsifiers and is a common additive in the food industry. It is also the starting monomer for the synthesis of a useful biodegradable polymer, poly lactic acid. The fermentative production of lactic acid can be achieved using cassava wastes/residues after acidic or enzymatic hydrolysis. Given its high content of starch and other organic matter, and its low cost, cassava fibrous residue was explored for its lactic acid production potential via solid substrate fermentation. A 6-day incubation in a reactor containing solid cassava residue with a moisture holding capacity of 60% resulted in a high yield of lactic acid (Ray et al., 2008). In another study, cassava pulp hydrolysates with a high glucose concentration (>100 g/L) were used as the carbon source in a fermentation by *Rhizopus oryzae* NRRL395, in which both lactic acid and ethanol were produced (Thongchul et al., 2009).

3.2.4. Succinic acid

Succinic acid, the end product of anaerobic fermentation by some anaerobic and facultative anaerobic microorganisms, is widely used in the synthesis of many important chemicals. An immobilized fermentation system, using cassava bagasse hydrolysate (CBH) and mixed alkalis, was developed to achieve economical succinic acid production by *Corynebacterium glutamicum*. The *C. glutamicum* strains were immobilized in a porous polyurethane filler. CBH was efficiently used as a carbon source and replaced more expensive glucose. With this strategy, 0.42 g succinic acid/(L h) was produced from 35 g glucose equivalents of CBH/L. An average of 22.5 g succinic acid/L was obtained from each batch fermentation, demonstrating the enhanced stability of the immobilized *C. glutamicum* cells (Shi et al., 2014).

3.3. Biosurfactant

Biosurfactants or microbially-derived surfactants can be produced from renewable feedstocks using a variety of microorganisms including bacteria, yeast and filamentous fungi. In comparison to synthetic chemical surfactants, they are of interest due to their high level of activity, specific action under extreme conditions, high degree of biodegradability, and numerous biological properties such as antimicrobial, antiviral, and antitumoral. Hence, they are suited for environmental applications such as bioremediation, dispersion of oil spills, and waste treatment. Among the many classes of biosurfactants, lipopeptides attract much attention because of their high surface activities and therapeutic potential. The lipopeptide surfactin, produced by *Bacillus subtilis* strains, is one of the most powerful biosurfactants discovered.

Studies have been carried out using carbon sources such as agricultural wastes and byproducts as substrates for biosurfactant production. The selection of waste as substrate involves the difficulty of finding a residue with a good balance of nutrients to support optimal growth and production. Agri-industrial wastes with high content of carbohydrates or lipids meet this requirement. Nitschke et al. (2004) found that natural *manipueira* medium showed minimum surface tension of 28 mN/m whereas the lowest value was 26 mN/m for decanted *manipueira*. Cassava flour wastewater offers promise as nutrients sources for biosurfactant production by *Bacillus* sp. Isolates and the use of natural *manipueira* could decrease the economics of process and residue treatment. Following their previous studies, Nitschke and Pastore (2006) investigated a biosurfactant synthesized by *B. subtilis* LB5a strain. The biosurfactant obtained from cassava wastewater showed high surface and interfacial tension reduction, small critical micelle concentrations, exhibited a high level of thermal stability and relatively stable to pH, and demonstrates a high level of tolerance to ionic strength and good emulsification capacity, suggesting potential commercial applications. The production of the biosurfactant compound on a pilot scale was also demonstrated to be a viable process (Barros et al., 2008).

3.4. Other value-added products

A number of studies have been carried out to provide more marketable products and overcome the ever-growing environmental problems. The bioconversion and value addition of cassava wastes and residues reduce the environmental concerns associated with crop and agri-industrial wastes, and simultaneously offer possible revenue sources to countries in South-East Asia, Africa, or Latin America (Ubalua, 2007).

3.4.1. Polysaccharide and its biodegradation

Pullulan, an extracellular biodegradable polysaccharide produced by *Aureobasidium pullulans*, consists of repeating units of maltotriose attached by α-(1 $\rightarrow$ 6) linkages. This inexpensive exopolymer is able to form oil-resistant, transparent, and oxygen-impermeable thin films. It can also be used as a starch replacement in low calorie food formulations in the food industry and as a packing material in the pharmaceutical industry. Sugumaran et al. (2014) investigated microbial pullulan production by *A. pullulans* using cassava bagasse as a solid substrate so as to reduce the cost of fermentation. Suitable conditions for the production of pullulan using cassava bagasse were: initial pH, 5.5; fermentation time, 4 days; moisture ratio, 1:2; nitrogen source, sodium nitrite; supplemental carbon source, mannose at a 5% (w/w) concentration.

3.4.2. Aromatic compound

The growing demand by consumers for natural food additives and other compounds of biological origin has focused attention on the flavor and fragrance compounds used in the food and cosmetics industries. Fruity aromatic compounds could be produced with cassava bagasse as the substrate in a solid-state fermentation using the yeast *Kluyveromyces marxianus*. A large amount of ethyl acetate, but also ethanol and acetaldehyde, was obtained (Medeiros et al., 2001). The fragrance compound, R-(+)-α-terpineol, characterized by a lilac-like odor, was successfully converted from R-(+)-α limonene in a reaction using liquid cassava waste as the culture medium (Marostica and Pastore, 2007).

3.4.3. Biofertilizer

The cassava peel was exploited for the phosphate biofertilizer production using phosphate solubilizing fungi by Ogbo (2010). Two fungi, *Aspergillus fumigatus* and *A. niger*, isolated from decaying cassava peels, converted cassava wastes by the semi-solid fermentation technique to phosphate biofertilizer. The isolates solubilized $Ca_3(PO_4)_2$, $AlPO_4$ and $FePO_4$ in liquid Pikovskaya medium, which was accompanied by acid production. Ground (0.5–1.5 mm) dried cassava peels served as carrier material in the semi-solid fermentation medium. The work aimed at the potential for the low-cost production of biofertilizers using affordable technology, locally available waste material and inocula.

4. Feasibility analysis

The various value-added processing and products of cassava industrial wastes as discussed could reinforce the profitability of related industries. However, the associated practicability estimation has to be taken into account before further implementation, through which the high-value products and promising bioconversion processes would then be selected from all the possibilities.

4.1. Bioethanol and bio-ABE production

Industrial wastewaters particularly from a food processing facility, such as the cassava industrial waste stream, could show promise when used as a substrate for solvent production by microorganisms. Apart from the lower raw material cost, the processing cost is likely to be lower than the regular solid cassava to ethanol process since the wastewater from the starch factory can be used instead of fresh water. However, main disadvantages of bioalcohol production probably limit its implementation: firstly, the total water usage is quite important, given that approximately 11.73 L of water is required per liter of bioethanol produced from cassava wastes (Fig. 1); secondly, high costs are resulted from the pretreatment, wastes generated by this pretreatment and the proper disposal of these wastes. From these standpoints, it is possibly not that economical to utilize cassava-based industrial wastes for the ethanol production in spite of the low price of feedstock.

4.2. Biomethane and biohydrogen production

The bioconversion of cassava starch or ethanol residues/wastewater into biomethane has been confirmed to yield as high as 250–350 mL CH_4/g VS. This was of the same methane potential as biomethane from starch or sugar crops. Total methane energy produced from anaerobic digestion of vinasse has been estimated to be around 1780–3340 Btu/L of ethanol produced (Nitayavardhana and Khanal, 2012). Hence, the bioconversion of cassava-based wastes into methane is appealing in both research and application. The anaerobic digestion of cassava-based industrial wastes could provide an opportunity to generate alternative gaseous fuel for heat/steam and electricity production for in-plant use. However, the economics and yield of methane generation may be challenged as a result of the large quantity of suspended solids in cassava industrial wastes/residues. Thereby, further work is needed with respect to pre-treating those residues (such as decantation) for the sake of solid separation and improving the bioreactors (like ASBR or UASB) to obtain greater efficiencies.

The high concentrations of greenhouse gases and the rapid depletion of oil and gas reserves have prompted many to search for eco-friendly energy alternatives. Hydrogen has been identified as a clean energy carrier and a renewable alternative to fossil fuel. Herein, from the standpoint of pollution control and resource recovery, it would be ideal to efficiently convert cassava industrial wastes/residues into both hydrogen and methane via the two-stage anaerobic digestion. Wang et al. (2011) obtained 74 mL H_2/g VS and 350 mL CH_4/g VS through the co-digestion of cassava stillage and sewage sludge, respectively, along with an energetic potential of ~16.1 MJ/kg VS. The biofuel yields and the resulted energetic potential mentioned above were close to those obtained from the corn-based substrate (Monlau et al., 2013); but the cost of feedstock was clearly much lower. However, as for the individual generation of gaseous biofuels, the bioconversion into biohydrogen is much more difficult than the biomethane production, leading to comparatively lower hydrogen yields from cassava-based industrial wastes. Additionally, the nutrients supplementation would largely increase the retail price of generated biohydrogen, and a competitive energy retail price of $2.84/MJ is impossible to achieve (Lucas et al., 2015).

4.3. Biochemical production

Among the discussed value-added bioproducts from cassava-based industrial wastes, it is found that, since 2006, the focus in research and application has been shifted from production of citric acid to other organic compounds, such as lactic acid and succinic acid. Worldwide, the average price of citric acid was $500–1000 per metric ton while lactic acid and succinic acid were sold at $1000–2850 and $2000–3000 per metric ton, respectively (Alibaba.com). The greater market potential drove the trend of production at lower cost.

The solid and liquid residues are generally high in organic contents, which could be used to produce value-added products for onsite use. For instance, the incorporation of lactic acid fermentation process into ethanol plants would enhance the profitability of the related industries. This strategy could improve the revenue up to $18–26 million annually with an increase of 55%. The lactic acid obtained could be further processed to poly lactic acid, a biodegradable plastic material with a higher market value than lactic acid. Accordingly, cassava-based ethanol plants are also expected to gain significant economic benefits by further bioconversion of stillage into lactic acid.

The bioproduction of succinic acid from cassava-based industrial wastes is considered to be economical and have a potential market. Currently, succinic acid is mostly produced by the chemical process, in which a major raw material cost is normally $1.027 per kg succinic acid. As for the biological process, the cost of raw material (taking glucose as an example) is reduced to $0.428 per kg succinic acid (Song and Lee, 2006). By using cassava industrial wastes as feedstock, the expense might be further decreased. It is thus obvious that the fermentative production of succinic acid from renewable resources is expected to have an economic merit and replace the chemical process. The market size of succinic acid attained from cassava-based industrial wastes/residues has not been well explored.

5. Future prospects

For the future research of cassava-based industrial waste bioconversion, a multi-disciplinary approach focusing on technical processes, extensive utilization of cassava lignocellulosic residues, advanced treatment of cassava biorefinery wastes, and combination of governmental policies are needed.

(1) The two-stage bioconversion process offers an appealing avenue for biorefinery to achieve directional substrate conversion in each stage. Favorite intermediates can be derived at the first stage through selective bioprocess; and separated stages for individually functional bacteria are connected to maximize the recovery of energy and biochemicals (Li and Yu, 2011). The co-generation of products will ultimately be facilitated along with the improved energy generation and reduced financial return.

(2) Fungal strains and the associated solid state fermentation have been widely employed to attain different bioproducts from cassava stillage or starch processing downstream. Additionally, on the one hand, the converted fungal biomass could be used as a source of protein in animal feed or fishmeal; on the other hand, high removals of organic matters indicate that the effluent after microbial biomass separation may then be recycled for in-plant use or directly discharged to the environment (Khanal et al., 2008).

(3) Extensive products could be derived from some physical or enzymatic pretreatment of lignocellulosic components. Thermoplastic materials, characterized as self-reinforced all-plant fiber composites, could be successfully obtained via the physical approach of mechanical activation (Liao et al., 2011) Besides, a enzyme of manganese peroxidase was reported to be achieved from cassava residues by solid state fermentation (Li et al., 2015). However, those extensive products still face challenges given their energy consumption, economical estimation and converting efficiency, and thereby, extended investigation and study are required.

(4) The leftovers resulting from some bioconversion of cassava-based industrial wastes may contain undegradable compounds such as black melanoidin, giving rise to negative environmental concerns. Thus, the sustainable strategy is to develop a holistic technology package in way of involving pollution treatment and resource reuse at the end of the biorefinery process. Suitable physiochemical or chemical processes may be taken into account as necessary treating techniques.

6. Conclusions

Bioconversion is a highly efficient and environmentally friendly strategy to cope with the abundant organic-rich cassava-based industrial wastes, including bagasse and stillage residues. Fermentation is well recognized as the most promising biological process for obtaining value-added products, including bioalcohol, biomethane, biohydrogen and organic acids, among many other potential products. Cassava-based agri-industries could employ biorefinery concept to produce value-added products from their residue streams; meanwhile the associated techno-economic analysis should be accompanied for the economic viability. Importantly, only with the coordination of technology development, governmental control and industrial implementation can the value of cassava wastes to the resource-energy chain be maximized.

Acknowledgements

Support for this research came from the National Science Foundation of China (Nos. 51178326 and 51738373), and the Fundamental Research Funds for the Central Universities.

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