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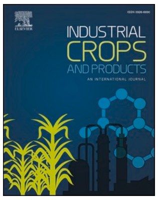

Dry biorefinery conversion of cadmium-contaminated rice grain and straw to ethanol with complete collection and recycling of cadmium

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ABSTRACT

Cadmium contaminated rice should be carefully treated by considering two aspects: full recovery of cadmium without risks of emission to environment, and energy balance between input and consumption. Separate treatment of rice grain and rice straw not only generates cadmium contained wastewater but also produces solid residue with livestock feed potentials. This study investigated a dry biorefining treatment to convert whole rice biomass (both grain and straw) into bioethanol at a reasonable energy balance and without solids residue potentials. The cadmium contained wastewater was significantly reduced and further completely evaporated into cadmium-free steam for recycled use in the treatment. The cadmium contained lignin solids were completely burned to evaporate the wastewater. The final cadmium content in combustion ash was enriched by 5–7 folds compared to raw rice biomass. The simulation showed that the heat generation from lignin residue combustion compensated for the energy requirement of wastewater evaporation. This study provides a fully converged treatment method of cadmium contaminated rice biomass on both cadmium and energy consumption with value added bioethanol production.

1. Introduction

Farmland soils are vulnerable to contamination of heavy metal elements such as cadmium (Cd), copper (Cu), chromium (Cr), lead (Pb), nickel (Ni), zinc (Zn), and mercury (Hg) owing to active industrial activities near agricultural land (Fang et al., 2016). Among these heavy metals, cadmium is more mobile and bioavailable than other heavy metals because of the cumulative property in human body (Murakami et al., 2009). Cadmium contamination has brought an awesome challenge to food safety in developing countries (Feng et al., 2020). According to the reports (Feng et al., 2020; Zhang et al., 2015), approximately 8% of farmland for grain cultivation was affected by cadmium contamination in China. The uptake of toxic cadmium from contaminated crops is associated with a large number of illnesses including kidney diseases, cancers, and cardiovascular diseases (Kaewnate et al., 2012; Kiran et al., 2022). The appropriate management and treatment of cadmium contaminated biomass are urgently needed for human health and ecosystem sustainability (Xiao et al., 2021).

Treatment of cadmium contaminated crops should enrich the cadmium level to which chemical treatments are applicable and avoid any risks of further cadmium emission, while the energy input of treatment should be minimized (Chai et al., 2022b). To meet this needs, there should be (i) no generation of any secondary contaminations to the environment by releasing cadmium contained water streams or precipitates; (ii) no transfer of cadmium compounds to the final metal-free product; and (iii) no additional high energy input to the treatment process. Direct combustion of rice and straw is a low efficient process and less acceptable in practical applications (Ma et al., 2020). Other thermochemical methods inevitably result in the dilution of already low cadmium content in crops and more difficulties in cadmium recovery (Chai et al., 2022a).

On the other hand, biorefinery processing is a promising method due to the efficient utilization of polysaccharides in crops and high cadmium enrichment after polysaccharides removal (Jiang et al., 2022; Xiao et al., 2021). Crop biomass contains a high amount of starch, cellulose, and hemicellulose components (60–80% starch in grain, ~60% cellulose and hemicellulose in straw) (Chuetor et al., 2021; Kim and Dale, 2004). These polysaccharides are capable of conversion into bioethanol as

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value added bioproduct and leaving enriched cadmium in lignin residue. The valorization of the cadmium contaminated agriculture biomass for energy production by biorefinery processing is therefore an attractive option, and could even turn phytoremediation into a profit-making operation (Van Slycken et al., 2013).

In regular biorefinery processing of heavy-metal contaminated plants, an adequate physical or chemical pretreatment such as steam explosion, acid pretreatment, alkaline pretreatment, and combined pretreatment (Cheng et al., 2018, 2019; Chuetor et al., 2021; Wu et al., 2020; Yu et al., 2022), is required before the enzymatic hydrolysis and microbial fermentation to overcome the bio-recalcitrance of raw lignocellulosic biomass (Wang et al., 2016). It is worth noting that a feasible biorefining solution of cadmium contaminated crop biomass should overcome several technical barriers: (i) grain conversion inevitably generates cadmium-rich distillers dried grain with solubles (DDGS) after fermentation and distillation, which is potentially used as illegal livestock feed; (ii) straw conversion to bioethanol is generally low efficient with the generation of a large amount of cadmium contained wastewater; (iii) high energy input is required for recovery of cadmium from wastewater stream.

In this study, cadmium contaminated rice was treated by dry biorefinery processing, in which rice grain and rice straw were simultaneously converted into bioethanol with the full recovery of enriched cadmium using heating energy from lignin residue combustion. The minor cadmium in rice biomass (in both rice grain and rice straw) was released to the aqueous phase and solid residue after enzymatic hydrolysis and ethanol fermentation and finally enriched in lignin residue. The heating energy of cadmium contained wastewater came from the combustion of lignin residue with the further enrichment of cadmium. This study provided a promising method of treating cadmium contaminated crop biomass and generally heavy metal contaminated biomass in phytoremediation as well.

2. Materials and methods

2.1. Raw materials

Rice straw and rice grain were harvested in Yancheng city, Jiangsu province, China in the fall 2015. Rice straw was milled to pass through the mesh with 10 mm in diameter. Rice grains were dry milled by passing through the 60 mesh screen with a bore diameter of 0.3 mm. The milled rice straw and rice grain were sealed in plastic bags and stored at room temperature until used. The starch content of rice grain was 76.06% (w/w). Cellulose, xylan, and lignin content of rice straw was 33.6 ± 0.1% (w/w), 19.7 ± 0.2% (w/w), and 19.3 ± 1.1% (w/w) based on dry weight, respectively.

2.2. Enzymes

The liquid commercial cellulase Cellic CTec 2.0 was purchased from Novozymes (Beijing, China). The filter paper activity, cellobiase activity, and protein content were 203.2 FPU/mL, 4900.0 CBU/mL, and 87.3 mg/g (Adney and Baker, 1996; Bradford, 1976; Ghose, 1987).

The thermostable α-amylase HTAA and glucoamylase GA-L NEW were purchased from Genencor (Wuxi city, China). Using soluble starch as substrate, the enzyme activity of HTAA and GA-L NEW was 22,000 U/mL and 100,000 U/mL, respectively, according to the manufacturer's instructions.

2.3. Microorganisms and media

Amorphotheca resinae ZN1 stored in China General Microorganism Collection Center (Beijing) Beijing, China with the registration number CGMCC #7452 (He et al., 2014), was used for biodetoxification.

Saccharomyces cerevisiae XH7 was used for ethanol fermentation (Li et al., 2016). The yeast extract peptone dextrose (YPD) medium containing 20 g/L glucose, 20 g/L peptone, and 10 g/L yeast extract was used for *S. cerevisiae* XH7 activation. The nutrients for ethanol fermentation contained 2 g/L KH_2PO_4, 2 g/L $(NH_4)_2SO_4$, 1 g/L $MgSO_4$, and 10 g/L yeast extract.

2.4. Biorefinery conversion of rice straw and rice grain

Milled rice straw was pretreated by sulfuric acid at high solids loading (~70%, w/w) to avoid the wastewater generation. The dosage of sulfuric acid was 3.2% (w/w) on dry rice straw base (Han and Bao, 2018). 1200 g (dry matter) of rice straw and 600 g of acid solution were co-fed into a 20-L pretreatment reactor. The pretreatment was kept at 175 ℃, 50 rpm for 5 min. The pretreated rice straw was discharged from the port at the bottom of the reactor in solid particle form. The acid solution and condensed water were absorbed onto rice straw with the water content of the pretreated rice straw at ~50% (w/w). No free wastewater was generated during pretreatment operation. The pretreated rice straw contained 349.3 ± 0.9 mg/g of glucan, 40.8 ± 1.2 mg/g of xylan, 26.0 ± 0.2 mg/g of glucose, 104.7 ± 0.2 mg/g of xylose, 17.6 ± 1.3 mg/g of glu-oligosaccharide, 31.1 ± 2.4 mg/g of xylo-oligosaccharide, 13.8 ± 1.5 mg/g of acetic acid, 4.4 ± 0.8 mg/g of furfural, and 4.2 ± 0.7 mg/g of HMF (5-hydroxymethylfurfural) based on dry weight.

The pretreated rice straw was neutralized with 20% (w/w) $Ca(OH)_2$ solution to pH value of 5.0–6.0, and then biodetoxified on solid to remove the free acetic acid, HMF, and furfural. The seed of the biodetoxification strain *A. resinae* ZN1 was prepared as previously described by Yi et al. (2019). The biodetoxification was conducted in a 15-L bioreactor at 28 ℃, 1.0 vvm for 48 h. The water content of biodetoxified rice straw was still around 50% (w/w), and the form of biodetoxified rice straw was still in solid particles.

Biodetoxified rice straw was used for ethanol production via simultaneous saccharification and co-fermentation (SSCF) in a 5-L bioreactor equipped with the helical ribbon stirrer at 30 ℃, 150 rpm for 96 h. The solid loading of rice straw was 30% (w/w). The cellulase dosage was 6 mg protein/g dry rice straw. The activation and seed preparation of the ethanol-producing strain *S. cerevisiae* XH7 were according to the methods described by Liu et al. (2018).

Separate hydrolysis and fermentation (SHF) was used for ethanol production from milled rice grain (McAloon et al., 2000). The rice grain hydrolysate was prepared by two-step liquefaction (α-amylase HTAA with the enzyme loading of 5 U/g dry rice grain at 90 ℃ for 0.5 h) and saccharification (glucoamylase GA-L NEW with the enzyme loading of 37.5 U/g dry rice grain at 50 ℃ for 5 h) under the solids loading of 15% (w/w) and well mixing.

2.5. Ethanol distillation and solid residue treatment in bench scale

Ethanol distillation was conducted in a glass column of 25 mm in diameter and equipped with a heat exchanger and spiral condenser (Zhang et al., 2021). The volumetric ethanol concentration in distillate was ~72% (v/v). The distillation stillage was dried in an oven at 105 ℃ to a constant weight. The dried solid residue was milled and burned into ash by complete incineration using thermogravimetric analyzer (TGA 8000, PerkinElmer, USA).

2.6. Aspen Plus simulation

Biorefinery process of rice biomass was simulated by Aspen Plus software (AspenTech, Cambridge, MA) based on NREL and our previously established models of bioethanol production (Humbird et al., 2011; Liu and Bao, 2017b). The handling capacity of the simulation was based on 300,000 metric tons of cellulosic ethanol annually with 8000 h of operation. Wastewater evaporation was calculated using the heat of lignin combustion heat. The heat loss of combustion was set to 15%. The calorific value of lignin residue was 17.12 GJ/ton determined by the method of Chinese National Standard No. GB/T 213–2008.

2.7. Analysis

The main compositions of rice straw were determined by a two-step acid hydrolysis method (Sluiter et al., 2008, 2012). The concentrations of glucose, xylose, ethanol, acetic acid, HMF, and furfural were determined by high-performance liquid chromatography (HPLC) (Liu et al., 2018). Starch content of the rice was determined by a rapid enzymic method (Holm et al., 1986). Practical ethanol yield was calculated according to the method proposed by Zhang and Bao (2012).

Cadmium was added to raw rice straw and rice grain at the dosage of 55 μg/g dry rice grain or rice straw in the form of sulfate, which is approximately equivalent to the cadmium content in general hyperaccumulator plant straw (Lin et al., 2017). The cadmium content was measured according to the method in Chinese National Standard No. GB/T 5009.15.

3. Results and discussion

3.1. Cadmium enrichment of rice grain and rice straw by dry biorefining

Whole rice biomass contains approximately equal amounts of rice grain and rice straw (Ji, 2015). As the first step, we investigated the separate conversion of cadmium contained rice grain and rice straw into bioethanol to test the dry biorefining concept and cadmium enrichment (Fig. 1).

For rice grain, the cadmium contaminated grain was milled, enzymatically hydrolyzed, and fermented into bioethanol. Rice grain hydrolysate was prepared at 15% (w/w) solids loading by cascade liquefaction (by α-amylase) and saccharification (by glucoamylase), then fermented into ethanol by *S. cerevisiae* XH7. The glucose concentration of rice grain hydrolysate was 96.1 ± 0.5 g/L and the final ethanol reached 48.3 ± 1.2 g/L with ethanol yield of 67.6% (Fig. 1a). The ethanol broth was distilled into the concentrated ethanol with the lignin solids containing stillage slurry. The water in the stillage slurry was evaporated for recycling, and the lignin residue was burned into the cadmium enriched ash. No cadmium was detected in the concentrated ethanol and the recycling water stream. The cadmium in the combustion ash was enriched to 292.2 ± 6.1 ppm, approximately 6.1 times higher than that in rice grain (Fig. 1b). One risk of this rice grain treatment was that the dried solid residues from rice grain, known as distillers dried grain with solubles (DDGS) contained excessive cadmium and could be used as livestock feed for profit. Furthermore, the energy input for stillage slurry evaporation did not balance the energy consumption because rice grain only generated a small amount of lignin fraction (less than 1%, w/w) (Mosier and Ileleji, 2020). Therefore, the additional energy input was inevitable.

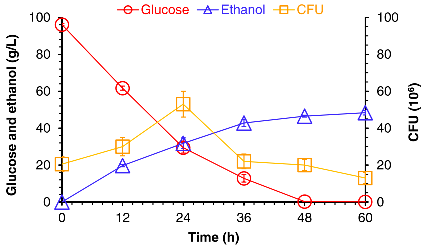
For rice straw, the cadmium contained rice straw was dry biorefined into bioethanol and the lignin residue was burned to generate heat energy used for wastewater evaporation. The dry acid pretreatment was applied under high solids content (~70%, w/w) without generation of wastewater and cadmium-containing exhaust gases. The pretreated solid rice straw was detoxified by *A. resinae* ZN1 to remove acetic acid, 5-hydroxymethylfurfural (HMF), and furfural inhibitors with the well preservation of sugars (loss less than 5%). The cellulosic ethanol was produced by simultaneous saccharification and co-fermentation (SSCF). The initial concentration of glucose and xylose was 81.3 ± 1.0 g/L and 31.8 ± 0.7 g/L in rice straw hydrolysate, respectively. The final cellulosic ethanol was 57.9 ± 1.4 g/L with the yield of 61.5% (Fig. 2a). Similar steps of ethanol recovery and water recycling were conducted as the grain ethanol (Fig. 1). No cadmium was released to ethanol or recycling water. The content of cadmium in combustion ash was enriched to 273.8 ± 9.8 ppm, which was 5.5 times higher than that in rice straw (Fig. 2b).

3.2. Whole cadmium contaminated rice biomass conversion by dry biorefining

When cadmium contaminated rice biomass was converted to ethanol, the most important consideration was to eliminate the potentials of further cadmium contamination and achieve the self-converged energy balance (without or with minimum additional energy input). The separate rice grain and rice straw conversion was not a promising method because the costs of energy, capital investment and operation at the fermentation stage were doubled with a potential risk of illegal use of rice DDGS as livestock feed. For this consideration, we combined the ethanol fermentation steps of rice straw and rice grain into one reactor (Fig. 3).

In this scenario, the DDGS from rice grain was mixed with the lignin residue of rice straw after fermentation and solid/liquid separation to essentially eliminate the potential of rice grain DDGS as livestock feed. The mixed rice grain and lignin were burned to generate the heat for the evaporation of the distillation stillage slurry. In the first step, the rice grain was firstly dry milled and hydrolyzed at 15% (w/w) solids loading into a high sugar hydrolysate; in the second step, the rice straw at the

(a) Ethanol production from cadmium contaminated rice grain



(b) Cadmium mass balance of rice grain

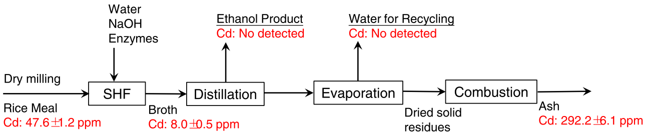
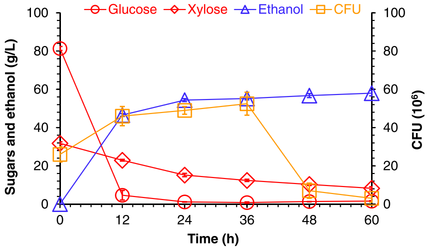


Fig. 1. Bioconversion and mass balance of cadmium contaminated rice grain into ethanol. (a) Ethanol production; (b) cadmium mass balance. SHF conditions: liquefaction stage, α-amylase 5 U/g DM, 15% (w/w) solids loading, 90 ℃, 0.5 h; hydrolysis stage, glucoamylase 37.5 U/g DM, 50 ℃, 5 h; fermentation stage, 20% (v/v) inoculation ratio, 37 ℃, pH 5.5.

(a) Ethanol production from cadmium contaminated rice straw



(b) Cadmium mass balance of rice straw dry biorefining process

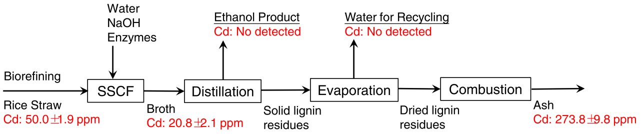
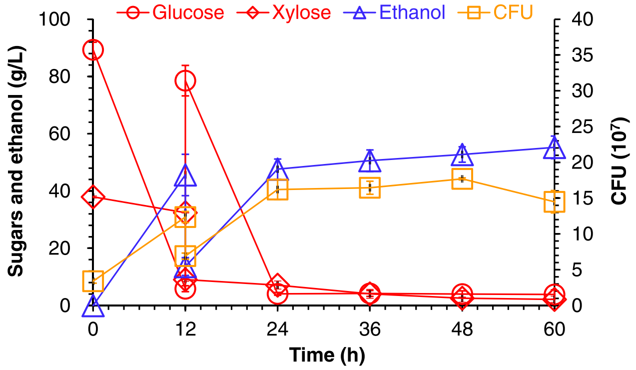
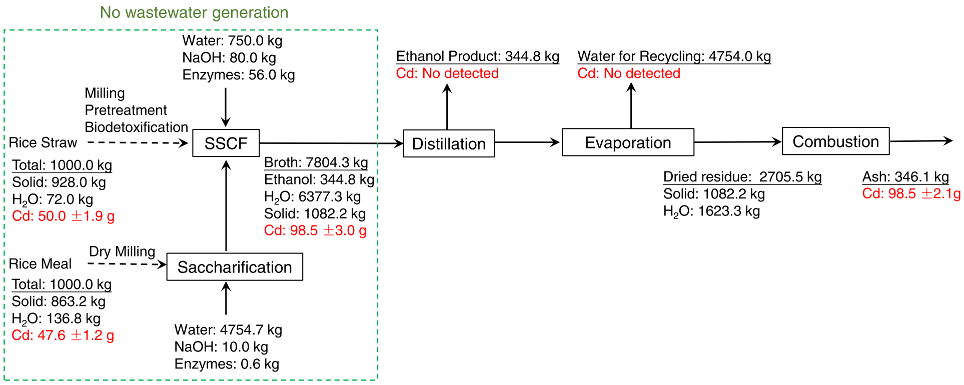


Fig. 2. Bioconversion and mass balance of cadmium contaminated rice straw into ethanol. (a) cellulosic ethanol production from rice straw; (b) cadmium mass balance. Pre-hydrolysis conditions: 30% (w/w) solids loading, 50 °C, pH 4.8, 12 h, cellulase dosage 6 mg total protein/g DM. SSCF conditions: 20% (v/v) inoculum ratio, 30 °C, pH 5.5.

(a) Ethanol production from cadmium contaminated whole rice biomass



(b) Overall mass balance of ethanol production from whole rice biomass



(c) Cadmium mass balance of whole rice biomass

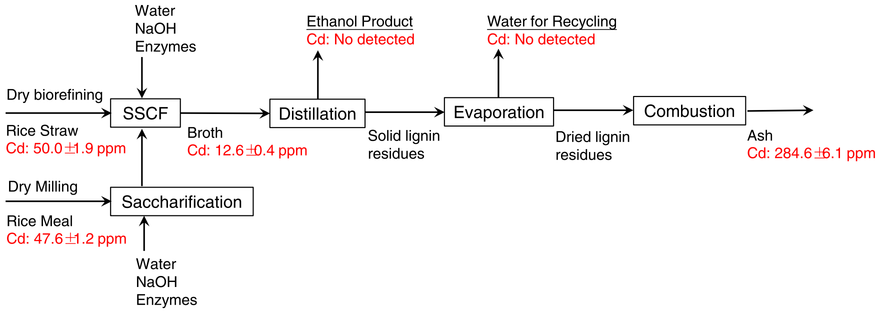


Fig. 3. Biorefining of whole rice biomass for ethanol production. (a) Ethanol production from cadmium contaminated rice straw and rice grain; (b) Overall mass balance of ethanol production from whole rice biomass; (c) Cadmium mass balance of whole rice biorefining. Prehydrolysis: 30% rice straw loading (w/w), 50 °C, pH 4.8, 12 h, cellulase 6 mg total protein/g DM. Fed-batch SSCF: 20% (v/v) inoculum ratio of *S. cerevisiae* XH7 seed, 30 °C, pH 5.5, 15% (w/w) solids loading of rice grain hydrolysate feeding at 12 h.

equal weight to the rice grain was pretreated, biodetoxified, and hydrolyzed at 30% (w/w) solids loading; in the third step, the *S. cerevisiae* XH7 seed was inoculated into the rice straw hydrolysate to initiate the SSCF for ethanol fermentation; in the final step, rice grain hydrolysate was fed into the rice straw SSCF at 12 h after the inoculation. The final ethanol production was 55.2 ± 3.9 g/L with the overall ethanol yield of 67.3% of the theoretical value from polysaccharides (cellulose, hemicellulose, and starch) (Fig. 3a). The CFU counting data showed that the combined SSCF of rice grain and rice straw had no negative effects on *S. cerevisiae* XH7 growth.

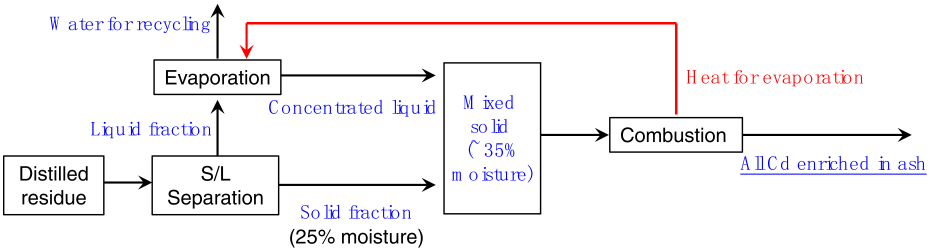
The overall mass balances of whole rice biomass to ethanol and the cadmium enrichment were shown in Fig. 3b. The whole rice biomass includes 1000 kg of rice grain and 1000 kg of rice straw was converted into 344.8 kg of ethanol. No cadmium release was detected in the ethanol product and the recycling water stream. The cadmium in the combustion ash was finally enriched to 284.6 ± 6.1 ppm, which was 5.7 and 6.0 times higher than that in rice straw and rice grain (Fig. 3c). This integrated biorefinery of rice straw and rice grain elevated the ethanol production efficiency and eliminated the risk of cadmium contaminated DDGS as livestock feed use.

3.3. Energy balance of recycling cadmium free water from distillation stillage of ethanol broth

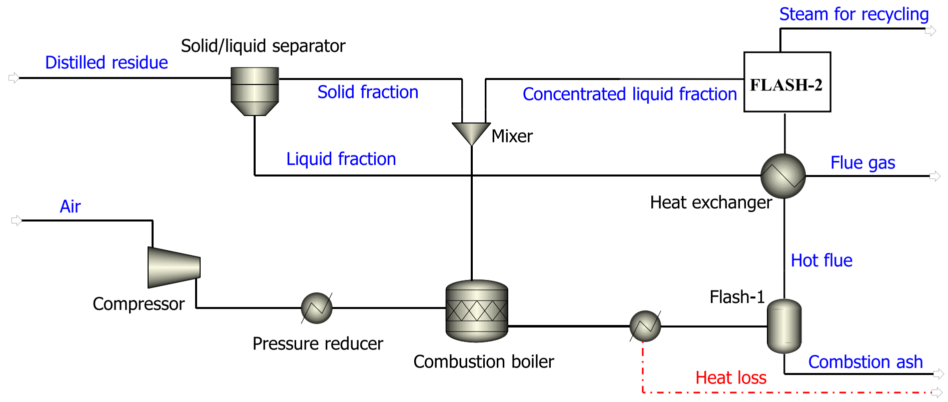
Cadmium contaminated whole rice biomass was converted into bioethanol by dry biorefining and the cadmium compounds were completely transferred into the liquid stillage stream after ethanol broth distillation and solid lignin residue after solid/liquid separation. The stillage slurry was evaporated into steam for recycling use (Liu and Bao, 2017a), and the lignin residue was burned as solid fuels. The cadmium was completely transported into the combustion ash. The essential prerequisite of this concept was the energy balance between the heating energy generated from lignin residue combustion and the energy consumption required for wastewater evaporation.

Fig. 4a shows the diagram of the treatment for the stillage slurry from ethanol distillation column of whole rice biomass broth. The stillage slurry from distillation column is filtrated into the lignin residue solids and the wastewater liquid by frame filter machine. The liquid fraction is evaporated into hot steam, and the small amount of cadmium contained residue is mixed with the lignin residue solids. The wet lignin residue solids contain considerable water content (25%–35%, w/w) but is still combustible (Humbird et al., 2011). Combustion of lignin solids generates the hot flue gases to heat the wastewater and leaves the

(a) Illustration of stillage slurry from ethanol distillation treatment



(b) Flowsheet of stillage slurry from ethanol distillation treatment



(c) Materials and energy balances in stillage slurry from ethanol distillation treatment

Rice biomass	Byproducts (ton/ton ethanol)		Heating energy (GJ/ton ethanol)		
	Wastewater	Lignin residue	Generated from lignin combustion	Required for wastewater evaporation	Energy balance
Grain only	26.35	2.59	28.87	60.05	-108.0%
Straw only	10.22	3.40	37.85	21.42	+43.4%
Whole biomass	18.50	3.13	41.10	41.11	~0.0%

Fig. 4. Flowsheet simulation of ethanol production on energy balance and cadmium enrichment. (a) Graphic illustration; (b) Flowsheet on Aspen Plus software; (c) Energy input of evaporation and output of lignin residue combustion.

combustion ash with enriched cadmium. The steam from wastewater evaporation is free of cadmium and recycled to the front-end biorefining steps. This concept is stimulated on Aspen Plus platform based on the experiment results (Fig. 4b). The energy balance results indicate that the heat from the combustion of lignin residue solids almost compensates the energy requirement of evaporation of wastewater when both rice grain and rice straw are processed simultaneously (Fig. 4c). For the separate biorefinery process of rice grain and rice straw, rice grain processing generates more wastewater and the lignin combustion does not generate efficient heating energy for recycling the wastewater, while

Table 1
Comparison of biorefinery processings for bioethanol production using heavy-metal contaminated biomass.

Biomass	Pretreatment	Ethanol fermentation			Wastewater (ton/ton ethanol)[a]	Heavy metal extraction (%)	Ref.
		Solids content (%, w/w)	Ethanol titer (g/L)	Ethanol yield (%)			
Canola	Alkali	~5	7.6	68.9	~157.9	/	Dhiman et al. (2016)
Napier grass	Steam explosion	~5	8.7–19.3	64.2–142.6	~49.2–109.2	/	Ko et al. (2017)
Miscanthus	Alkali	~5	/	~35–50	/	73–96	Cheng et al. (2018)
Wheat straw	Alkali and acid	~5	/	~12–16[b]	/	~100	Cheng et al. (2019)
Willow	Steam explosion	~5	/	~65	/	~80	Ziegler-Devin et al. (2019)
Rice	Dry acid	30	55.2	67.3	13.8	~100	This study

[a] Includes all wastewater generated from pretreatment and ethanol fermentation, excludes the washing and recycling steps.
[b] The unit of ethanol yield is based on the percentage of dry straw.

the rice straw processing gives sufficient energy but the ethanol production and process economy are reduced.

Table 1 summarized the different biorefinery processings for bioethanol production using heavy-metal contaminated biomass. Dry biorefinery processing significantly reduces the wastewater generation by applying high solids loading pretreatment and fermentation, thus contributing to the fully converged treatment of cadmium contained wastewater by lignin combustion and evaporation.

Nevertheless, some limitations still present in dry biorefining processing. One of the technical difficulties in this concept is the volatilization of cadmium during combustion. Cadmium exists at least in three forms, solid combustion ash, solid particles in flue gases, and gaseous compounds in flu gas (Dastyar et al., 2019). The very volatile property of cadmium at combustion temperature (~800 ℃ or above) and flue gas temperature (250–300 ℃) will generate cadmium contained fine solids particles or gases, and the essential measures should be taken for full recovery of these combustion byproducts (Kovacs and Szemmelveisz, 2017; Poškas et al., 2018).

Cheng et al. (2019) reported that the higher cadmium addition led to the higher soluble sugars accumulation level in wheat straw. In our previous studies, we also have investigated the possibility of converting the soluble sugars into final product (Dong et al., 2019; Han et al., 2018). Several reasons limited the practical contribution of soluble sugars to the overall process: (i) the soluble sugars content generally is low and not stable; (ii) direct extraction of the soluble sugars leads to a low biomass solids loading in hydrolysis or fermentation steps; (iii) soluble sugars are easily converted to furan aldehydes (furfural and HMF) in pretreatment step.

Yu et al. (2022) described the biosorbents preparation using remaining solid residues from ethanol fermentation and pectin extract from citrus peels by crosslinking reaction. It is a promising approach to prepare active biosorbent preparation using the solid residues generated from dry acid pretreatment and ethanol fermentation. But the current study aims to fully converged treatment of cadmium contaminated biomass without the possibility of secondary contamination by eliminating the waste streams generation. Therefore, all of the cadmium contained lignin residue was combusted for wastewater evaporation to achieve the processing energy balance.

Cheng et al. (2018) reported that *Miscanthus* showed significantly reduced cellulose levels and features (cellulose crystalline index and degree of polymerization) with much increased hemicellulose and pectin contents due to the large cadmium accumulation, which significantly improved the enzymatic hydrolysis yield at ~5% (w/w) solids loading after alkaline pretreatment. Straw was pretreated by dry acid pretreatment method under harsh conditions (175 ℃, 5 min), in which over 90% of hemicellulose was hydrolyzed into xylose and over 90% of cellulose was converted to glucose in the consequent enzymatic hydrolysis (He et al., 2014). The contribution of Cd existence was certainly negligible. In the future work, we will further investigate whether the Cd accumulation in biomass could improve the enzymatic hydrolysis at high solids loading in the context of dry biorefining process.

4. Conclusions

A dry biorefining process was used to convert cadmium contaminated rice biomass into bioethanol with fully converged cadmium and well balance energy consumption. Dispersed cadmium in rice biomass was finally enriched into combustion ash. The heat from the combustion of lignin residue compensated for the energy requirement of evaporation of wastewater. This study not only provides a secure process for the valorization of heavy metal contaminated biomass for biofuel production, but also verifies the possibility of fully converged treatment of wastewater in the lignocellulosic biorefining process.

CRediT authorship contribution statement

Shuai Shao: Methodology, Validation, Visualization, Investigation, Writing – original draft. **Bin Zhang:** Visualization, Data curation, Writing – review & editing. **Ya Wang:** Modeling, Validation, Visualization. **Tao Han:** Investigation, Validation. **Jie Bao:** Conceptualization, Supervision, Funding acquisition, Project administration, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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