



ELSEVIER

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

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


Effective utilisation of cassava bio-wastes through integrated process design: A sustainable approach to indirect waste management

K.S. Tumwesigye^{a,b}, L. Morales-Oyervides^a, J.C. Oliveira^a,
M.J. Sousa-Gallagher^{a,*}

^a Process & Chemical Engineering, School of Engineering, University College Cork, Ireland

^b National Agricultural Research Laboratories, NARO-Kawanda, Uganda

ARTICLE INFO

Article history:

Received 30 November 2015

Received in revised form 4 March 2016

Accepted 10 March 2016

Available online 17 March 2016

Keywords:

Cassava

Process integration

Modeling

Optimal design

Waste management

Sustainability

ABSTRACT

An integrated process design, which can be applied in small-to-medium batch processing, was proposed. The process is based on the exploitation of intact (whole) cassava root, through optimisation of simultaneous release recovery cyanogenesis downstream processing for sustainable wastes minimisation and packaging material development.

An integrative seven unit process model flow was considered in the process design modelling. Using the release process models, it was possible to predict the maximum yield (45.8%) and the minimum total cyanogens (0.6 ppm) and colour difference (4.0) needed to avoid wastes and unsafe biopolymer derivatives. The process design allowed saving on the energy and water due to its ability to reuse wastewaters in the reactions and release processes. Drying rates, Scanning electron micrograph, Differential scanning calorimetry, Water vapour transmission rate and Fourier transmission infrared spectroscopy analyses have demonstrated the practical advantage of laminar flow hood air systems over oven-drying heat for integrated process design.

Thus, the integrated process design could be used as a green tool in production of cassava products with near zero environmental waste disposal.

© 2016 The Institution of Chemical Engineers. Published by Elsevier B.V. All rights reserved.

1. Introduction

The continued demand for waste-free environments coupled with the unregulated and high costs of proper waste management, requires customised, robust, and inexpensive solutions to ensure sustainable waste minimisation. Currently, cassava by-products are increasingly contributing to the global hazardous wastes, industrial disasters and environmental health risks (Adeola, 2011; Kolawole, 2014). The poisonous nature inherent in most bitter cassava cultivars (Tumwesigye et al., 2016) contributes to some extent to environmental health risks, and this has been exacerbated by the decline of suitable

disposal sites. The composition of cassava biopolymer derivatives is shown in Table 1. Previous research focus has been on minimising the environmental cassava wastes by developing them into valuable products (Ezejiolor et al., 2014; Raabe et al., 2015; Tumwesigye et al., 2016; Versino et al., 2015). However, with increasing population and small-to-medium processing (SMP) facilities of cassava, into starch and other products, for food, feed, and non-food applications, waste streams such as waste solids (WS) and wastewaters (WW) will be serious hazards. Cassava waste solids consist of the peel, internal root centre fibre (xylem bundles) and unwanted discard solids. Additionally, the above interventions are unilateral processes

* Corresponding author at: University College Cork, Process & Chemical Engineering, School of Engineering, Food Science Building, Room 308, College Road, Cork, Ireland. Tel.: +353 021 4903594; fax: +353 021 4270249.

E-mail address: m.desousagallagher@ucc.ie (M.J. Sousa-Gallagher).

<http://dx.doi.org/10.1016/j.psep.2016.03.008>

0957-5820/© 2016 The Institution of Chemical Engineers. Published by Elsevier B.V. All rights reserved.

Table 1 – Composition of major cassava biopolymer derivatives.

Derivative	Total waste (%, w/w) ^a	Peel waste (%, w/w) ^b
Dry matter	30.13	
Ash	7.00	4.5
Crude protein	3.50	
Crude fibre	10.00	
Ether extract	12.00	
Neutral detergent fibre	52.00	
Acid detergent fibre	25.00	
Acid detergent lignin	11.00	
Cellulose	14.00	37.90
Hemicellulose	27.00	23.90
Holocellulose		66.00
Lignin		7.50
Hot water solubility		7.60
1% NaOH solubility		37.50
Moisture content		14.00

^a Adeola (2011).
^b Aripin (2013).

that are not integrated leading to increased waste costs. The WS and WW are usually characterised by acidification due to the hydrolysis of total cyanogens producing hydrogen cyanide which is toxic to household animals, fisheries and other organisms (Kolawole, 2014). Furthermore, serious environmental pollution such as foul odour and pathogen-suspended solid carriers are other components of WS and WW leading to surface and underground water and soil contaminants (Ubalua, 2007). Moreover, the greater numbers of SMP units, their poor and more time-consuming processing methodologies, and limited disposal routes, override WS and WW management capacities.

The inherent traditional processing nature of SMPs does not support process integration for the minimisation of waste solids (WS) and wastewaters (WW). Some approaches have been employed to minimise environmental accumulation of cassava WS and WW. Examples of the strategies used currently include cultivar selection for minimisation of residue generation and water consumption in the industrial processes (Maieves et al., 2011), bagasse for bioprocessing of organic acids, ethanol, aroma (John, 2009) and root peel production of biocomposites (Versino et al., 2015). Unfortunately, the underlying high processing costs, energy and time of the above and other strategies complicates further WS and WW minimisation. These strategies do not incorporate holistic approaches to process design, adding further constraints to sustainable WS and WW minimisation management. A sustainable cassava WS and WW minimisation solution can be approached by optimal design models of individual processes, as drivers that give best interface leverages. Examples of such leverages could be achieved by applying cassava wastes in packaging materials production using an integrated process design.

The integrated methodologies which emphasise process optimisations and consider production component synergisms and mathematical models are highly regarded as sustainable solutions for waste minimisation. The process design methods previously employed had been reported as graphical-based techniques such as water pinch' analysis and mathematical optimisation (Majozi and Gouws, 2009). While these techniques offer a striking approach for waste minimisation in large scale processing systems, there is need to develop simple attractive substitute process design that

address environmental WS and WW of dominant cassava SMPs from a sustainable technological point of view.

The key aim of the study was to develop and optimise an integrated process design (IPD) for effective use of cassava wastes, and development of sustainable packaging materials. Specifically, the study investigated an optimal structure of simultaneous release recovery cyanogenesis (SRRC) using individual processes and process models. The purpose was to gain insight into important individual processes and models that would facilitate SRRC integration in order to maximise WS and WW utilisation while minimising water solvent usage. It was anticipated that such models would exploit individual process interfaces, bringing in synergies and lead to sustainable processes.

The study comprised process integration applicable to small-to-medium-scale batch processing of bitter cassava that contributes in part to accumulated environmental wastes. A case study for the development of packaging films demonstrating IPD improvement and application potential was undertaken.

2. Experimental

2.1. Model development and optimisation studies

2.1.1. Waste derivatives yield

The objective was to develop an all-embracing optimised waste yield model and provide a foundation from which other process models could be optimised, and support integration into holistic design. Waste derivatives were processed using the root biomass of intact bitter cassava following the method described by Tumwesigye et al. (2016) without modifications. The term, “waste derivatives” refers to the product recoveries from waste solids and waste water. Cassava biopolymer derivatives, comprises the major polymers (primary metabolites) of importance for the development of biobased materials, and include holocelluloses, lignin and starch. Processing intact root using SRRC produces fibre-rich derivative powder which has been found to deliver better mechanical and barrier properties (Tumwesigye et al., 2016).

The yield model was developed using a Box–Behnken-design by varying parameters namely buffer (0, 2, 4%, w/v), cassava waste solids (15, 23, 30%, w/w), and extraction time (4, 7, 10 min) based on experimental design (Table 2a). Data analysis was performed as described in Tumwesigye et al. (2016) using Statistica 7.1 software (StatSoft Inc., Tulsa, USA) The resulting process model was optimised with multi-response desirability model (Eq. (1)) (Derringer, 1980).

$$D = [d_y(Y)]^{1/n} \quad (1)$$

where D , over all desirability; Y , yield (%); $d_y(Y)$, yield desirability function; n , responses ($n=1$); $d_y(Y)=0$, perfectly undesirable; $d_y(Y)=1$, perfectly desirable.

2.1.2. Total cyanogens and colour

Total cyanogens (TC) was analysed using the kit developed by Bradbury et al. (1999), and colour estimated by the colour difference (ΔE) using CR-400 Chroma Metre, Konica Minolta Sensing Japan. The TC and ΔE models were developed using a Box–Behnken-design with buffer (0, 2, 4%, w/v), cassava waste solids (15, 23, 30%, w/w), and sodium bisulphite (1, 2, 3%) based on experimental design (Table 2b). Their process

Table 2 – Box–Behnken experimental design processing parameters used in biopolymer derivatives production. Biopolymer yield (a) and total cyanogens and colour (b).

(a)			
Variables	Coded levels		
	x_1 (-1)	x_2 (0)	x_3 (+1)
^a Buffer (% w/v)	0	2	4
^b Waste derivative (% w/w)	15	23	30
Extraction time (min)	4	7	10
(b)			
Variables	Coded levels		
	x_1 (-1)	x_2 (0)	x_3 (+1)
Buffer (% w/v)	0	2	4
Waste derivative (% w/w)	20	30	40
Sodium bisulphite (%)	1	2	3

^a Ionic buffers consisting of molar sodium chloride (NaCl) and millimolar.
^b Sulphuric acid (H₂SO₄) solutions (NaCl:H₂SO₄, 60:1 M), pH 5.5.

models were optimised using multi-response desirability model (Eq. (2)) (Derringer, 1980).

$$D = [d_{TC}(TC) \times d_{\Delta E}(\Delta E)]^{1/n} \quad (2)$$

where D , overall desirability; TC , total cyanogens (ppm); $d_{TC}(TC)$, total cyanogens desirability function; ΔE , colour change; $d_{\Delta E}(\Delta E)$, colour desirability function; n , responses ($n=2$); $d_{TC}(TC)$ and $d_{\Delta E}(\Delta E)=0$, perfectly undesirable; $d_{TC}(TC)$ and $d_{\Delta E}(\Delta E)=1$, perfectly desirable.

2.2. Evaluation of integrated process design

Integrated process design for cassava waste solids (WS) and wastewater (WW) minimisation and packaging film

development was studied using a conceptualised process model flow depicted in Fig. 1.

Processes inherent within the root SRRC and those externally sourced, were defined, described, analysed and used in the design of integrated downstream processing model. The criterion for selection and analysis was based on the added value each process would contribute to utilisation of wastes and greatly facilitated WS and WW minimisation at low cost, energy and time. In particular, special attention was paid to reaction processes in the release and recovery through wastes recovery, total cyanogens reduction and colour improvement after pulping.

Processing intact root using SRRC produces fibre-rich derivative powder which has been found to deliver better mechanical and barrier properties (Tumwesigye et al., 2016).

2.2.1. Biopolymer derivatives drying rate studies

The drying rates of the biopolymer derivatives, were performed by using either a conventional oven-drying (Memmert Universal Oven U, Model 600, Germany), or a laminar flow hood air system (rangehood) (Kottermann High Performance Lab Hood Cupboards, UK). The loss in weight of the derivatives was measured every 30 min until a constant weight was reached. The air flow velocity, temperature and relative humidity (RH) of the rangehood was 0.62 m/s, at 20–22 °C, and 50–60%RH, respectively, while those of the oven was 0.2 m/s, 25 °C and 50–60%RH. The airflow velocity was monitored using an environmental monitor (Solomat 510e, UK). All the measurements were taken in triplicate and the drying rates comparisons were considered using the constant rate period.

2.2.2. Biopolymer derivatives microstructure

Biopolymer derivatives microstructure (DM) characteristics were examined using Scanning Electron Microscope (SEM), JSM-5510 (Joel Ltd., Tokyo, Japan). A derivatives powder sample was placed on stubs using double-sided carbon tape to form a very thin layer and leaving a space on either side of the strip to allow clear observation of surfaces and cross section.

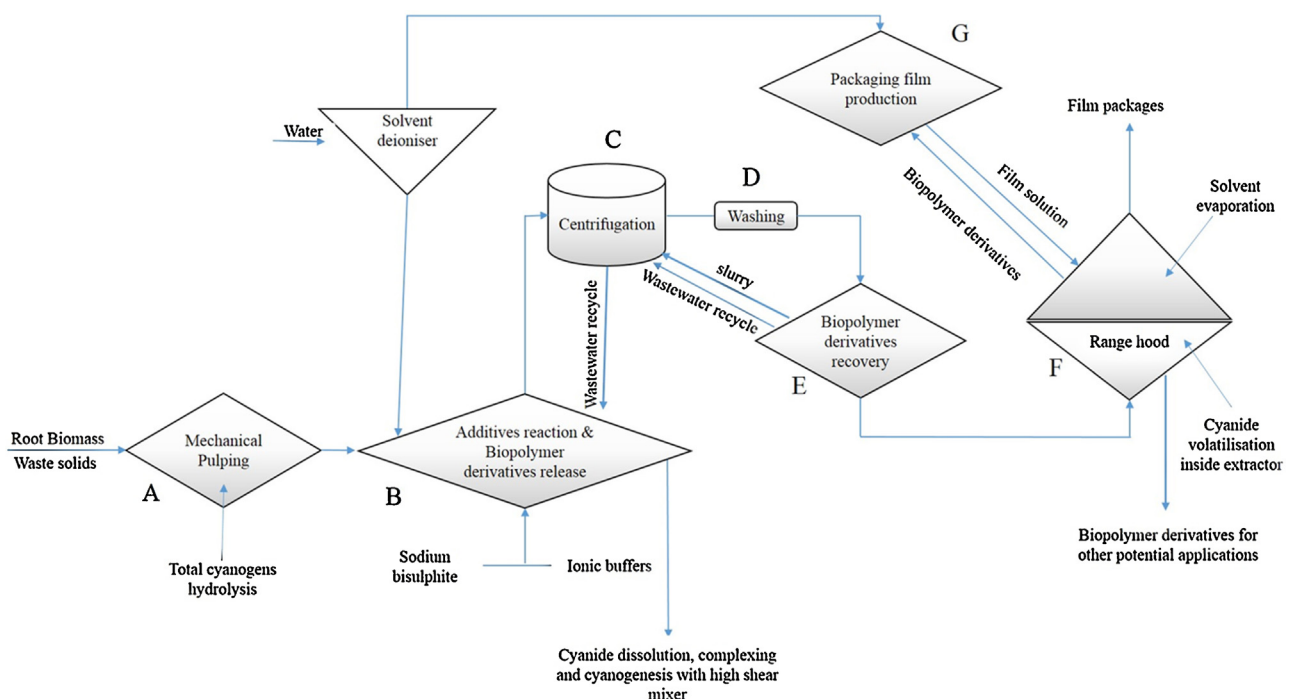


Fig. 1 – Generalised integrated process design model. A, B, C, D, E, F, G represent unit operations.

Prior to capturing SEM images, powder stubs were splattered with a thin layer of gold. Powder stubs were subjected to a focus magnifications as high as 20,000× and images capture between 200× and 30,000× magnification and intensity of 5 kV.

2.2.3. Film formulation

Intact bitter cassava films were formulated and optimised as described by [Tumwesigye et al., 2016](#). Biopolymer derivatives (3g) and glycerol (30%) were dissolved into deionised water to make 100% solution, mixed by magnetic stirrer (5 min) and heated to 70 °C until a clear solution was obtained. The cycle lasted 25 min. The solution was cast onto circular dishes ($d = 14$ cm) and dried in a rangehood (airflow velocity, 0.62 m/s). The dried films were easily peeled off and kept for further use.

2.2.4. Film thermal analysis

Differential scanning calorimeter (DSC 200 F3) was performed by weighing a derivative sample (10 mg) into aluminium pan, sealing and treating it to heating-cooling cycle from 20 °C to 250 °C at 10 °C/min. Experiments were performed in triplicate.

Thermogravimetric analysis (TG Analyser, Spectrum 500) was performed by heating a derivative sample between 30 °C and 500 °C, at 20 °C/min using nitrogen at 60 mm/min. Experiments were performed in triplicate.

2.2.5. Film water vapour transmission rate

Water vapour transmission rate (WVTR) was measured gravimetric using [ASTM E96/E96M-05 \(2005\)](#). A sample was mounted between acrylic permeation cells, containing previously dried (105 °C, 9h) 4g CaCl₂ (0%RH), enclosed in a humidity-controlled (95%RH) container placed in an incubator (38 °C). The changes in weight of the cell were recorded every 2h for 10h and data obtained was used for WVTR calculation. Experiments were performed in triplicate.

2.2.6. Film chemical characterisation

Fourier transform infrared spectroscopy (FTIR) was performed by using UV/Vis spectrum one spectrometer (Perkin Elmer Lambda 35, USA). The changes in spectra intensities were measured between 4000 and 400 cm⁻¹ at 4 cm⁻¹ resolution in the transmittance mode with 30 scans at room temperature. The averages of three samples were used plotting the spectra.

3. Results and discussion

3.1. Integrated process design description

The cassava simultaneous release recovery cyanogenesis (SRRC) downstream processing for waste solids (WS) and wastewater (WW) minimisation integrated with packaging film development comprised seven operation units ([Fig. 1](#)). The concept was intended to minimise wastes by directly processing fresh intact bitter cassava root biomass and avoid underlying costs, energy, time, intended and unintended disposal efforts, of additional alternative processes for waste management. Process modelling and optimisation was intended to determine the most economic SRRC process design for sustainable use of bitter cassava into value added products and minimise wastes. Particular focus of modelling and optimisation was on early stages of the design (pulpung and reactions/release) because it holds most important processes to enhance modifications and release of wastes and associated compounds.

3.1.1. A: Mechanical pulping

In order to attain sufficient total cyanogens hydrolysis and finer fibrous waste solids (30–50 μm) for production of good quality and non-toxic pulp, an efficient mechanical pulping was required. This was achieved by ensuring that the pulping efficiency of ≥90% was applied in pulping process using time-dependent model ([Eq. \(3\)](#)). This is the first part of the process which involves crushing the intact root into much finer pulp using high shear rate pulpers. The purpose of high shear grating at this stage is to improve the pulp texture, and reduce extraction time in the subsequent release stage. Graters of this magnitude are suitable and commonly used by small and medium processors. This was used as the initial pulping stage in this study. Additionally, the analytical grinder (IKA Yellowline-R A 10, Germany), which attains 18,000 RPM was used in the secondary process, resulting in mass texture with nominal size of 30–50 μm (determined using the corresponding micron size sieves).

The recalcitrant nature of most cellulose fibre mass succumbs at high shear rates, with the remaining pulp being relatively insignificant. Furthermore, cassava biomass has relatively softer cellulosic fibres when compared to other woody crops/plants. This could also explain the finer powder (30–50 μm) that was obtained in this study. Besides, with 30–50 μm size mass, all the total cyanogen is released.

$$\text{Pulping time, s} = 36144.36 + 33.11v - 845.74\eta_g + 0.01v^2 + 4.97\eta_g^2 \quad (R^2 = 0.95) \quad (3)$$

where v , pulper drum velocity; and η_g , pulping efficiency.

In pulping process, the breakdown of cells activates hydrogen cyanide release from cyanoglucoside linamarin, a precursor of cyanide related compounds ([Fig. 2a](#)).

The hydrolysis of linamarin into cyanohydrins and hydrogen cyanide under the influence of linamarase enzyme ([Fig. 2a](#)) has been widely reported as important factor in cyanogenesis process ([Cereda and Mattos, 1996](#); [Crowe and Bradshaw, 2014](#)). Cyanogenesis (loss of total cyanogens) was examined between intact and peeled during pulping process, and was found to vary greatly when pulping efficiency was increased. As shown ([Fig. 2b](#)), intact roots demonstrated higher total cyanogens loss than the peeled roots, further confirming the intrinsic hydrolysis by the intact root as previously reported ([Tumwesigye et al., 2016](#)).

The natural occurrence of high linamarin and linamarase contents in the root cortex (peel) than in the parenchyma (edible portion) makes it easy for detoxification using standard processes.

3.1.2. B: Reaction and release

The goal of the reaction and release was to improve extraction and yield of biopolymer derivatives. Addition of ionic buffers (sodium chloride and dilute sulphuric acid) helped to release the biopolymer derivatives. Nearly all the root biomass was converted into the derivatives when the model and optimised yield was applied in the extraction ([Eq. \(4\)](#), [Table 3](#), [Fig. 3](#)).

$$\text{Yield, \%} = 27.55 + 21.81b + 1.21w - 2.27t - 1.10bw - 0.62bt + 0.16wt - 4.95b^2 - 0.06w^2 - 0.11t^2 + 0.017bw^2 + 0.13b^2w + 3.59b^2t \quad (R^2 = 0.91) \quad (4)$$

where b , ionic buffer; w , waste solids and t , extraction time.

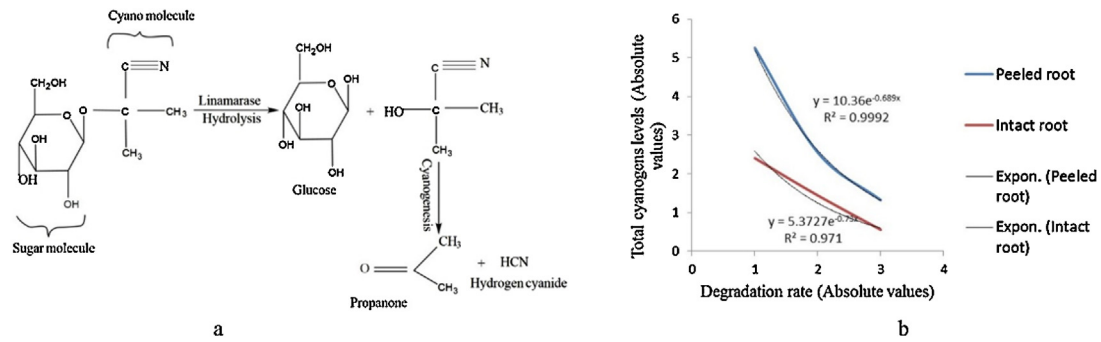


Fig. 2 – Total cyanogen behaviour during pulping stage. Hydrolytic pathway (a) and comparison of degradation rate between intact and peeled cassava root (b).

Parameters	Experiment levels			Optimal derived parameter values	Properties		
					Yield, %		Desirability
					Optimum	Range	
Buffer (% v/v)	0.0	2.0	4.0	4.0	45.8	15.0–55.0	1.0
Waste (% w/w)	15.0	23.0	30.0	30.0			
Extraction time, min	4.0	7.0	10.0	10.0			

The root contains both linamarin and linamarase including low lotaustralin levels, all of which constitute total cyanogen or cyanogenic glucosides. The two main root parts, cortex (peel) and parenchyma (edible) contain these cyanogenic glucosides, with the former containing more levels than the latter. During SRRC process, involving pulping and release, the linamarase hydrolyses linamarin under high shear force to release hydrogen cyanide and the ketones. In the release process, both ionic buffer and bisulphites are functionalised in the solution, and at low pH (5.5–6.0), the bisulphite has the affinity for the ketones, which are subsequently made unavailable. This creates a gradient for further release of more hydrogen cyanide. This could explain the substantial detoxification of the slurry. There is also another possibility

that the residual sulphur reacts with hydrogen cyanide to form a more harmless thiocyanate (SCN⁻) compound. During traditional processing, there are short-cuts which fail to fully detoxify cassava. This is the novelty that the SRRC presents in this study.

Furthermore, the purification of biopolymers from impurities of special interest, total cyanogens (TC) and colour, were accomplished by reaction additives. Reactions between TC (from the pulping stage) and sodium salts of bisulphite and chloride further ensured that more derivatives were freed from total cyanogens, as shown by the reaction Eqs. (5) and (6). Another important impurity of concern is the colour, which is the liberated colour of peel biomass after derivative extraction. This was handled by employing food grade sodium bisulphite

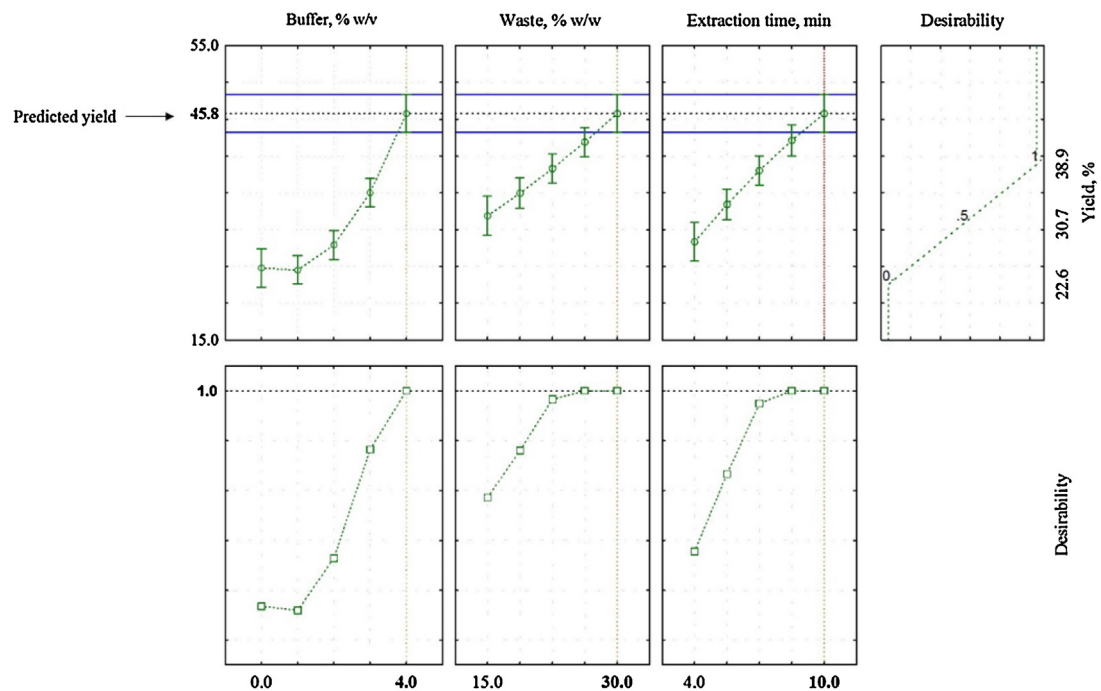
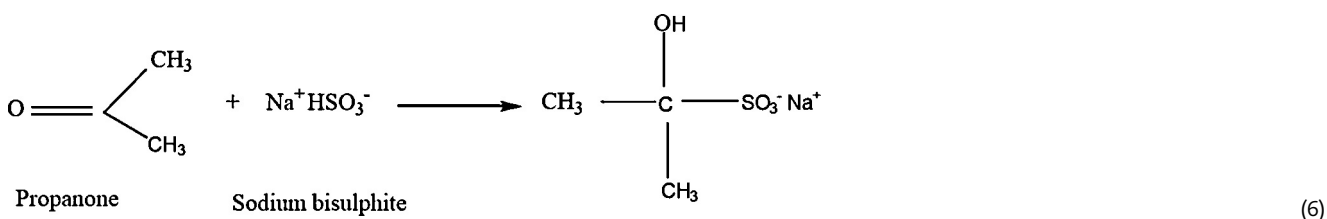


Fig. 3 – Global desirability analysis of yield.

(SB), in addition to ionic buffers, which has been widely used to bleach coloured products such as paper pulp (Guo et al., 2013) and food (Hartert, 2007). The SB, under acidic conditions, acts as a reducing agent and in the process is oxidised (Eq. (3)) (Guo et al., 2013).



In order to improve the release and reaction, TC and colour were modelled and optimised as shown (Eqs. (7) and (8), Table 4, Fig. 4). The individual and global desirability showed that the solution for TC and colour reduction in biopolymers could be feasible by obtaining 0.6 ppm and 4.0 when applying buffer (b), 4.0% (v/v); waste solids (w), 18.8% (w/w); and sodium bisulphite (s), 3.0% respectively at the release stage.

$$\begin{aligned}
 \text{Total cyanogens, ppm} = & -9.65 - 0.65b + 1.59w - 0.52sb \\
 & - 0.50bw + 1.07bsb - 0.03wsb + 0.93b^2 \\
 & - 0.03w^2 + 0.04sb^2 + 0.01bw^2 + 0.05b^2w \\
 & - 0.28b^2sb \quad (R^2 = 0.96) \quad (7)
 \end{aligned}$$

$$\begin{aligned}
 \text{Colour change, } \Delta E = & 10.08 - 0.26b + 3.31w - 0.07sb - 0.02bw \\
 & + 1.00bsb - 0.00wsb + 0.71b^2 - 0.01w^2 \\
 & + 0.24sb^2 + 0.00bw^2 + 0.02b^2w \\
 & - 0.02b^2sb \quad (R^2 = 0.96) \quad (8)
 \end{aligned}$$

3.1.3. C & D: Centrifugation and washing

Centrifugation and washing design stages were aimed at refining the biopolymer derivatives, separation of wastewater (WW) and dilutions of hydrogen cyanide and bisulphite compounds. For the purpose of saving energy on deionising water and maximise resource utilisation, WW was recycled between centrifugation, washing and release stages. The WW was concurrently used to further aid the reaction stage and refine the biopolymers. This is because WW still contained bisulphites and ionic salts, which were sent back to reaction and release stage as a reaction solution for efficient TC and colour removal. Frequent washing and filtration eliminated a bigger proportion of cyanide-bisulphite complexes since the latter ionise in water to form soluble complexes.

In order to quantify the volume of solvent recycled in release-centrifugation-washing-recovery cycle, the supernatant retained after the slurry was separated and measured. Cumulative volumes were measured from the frequency of the cycle. The supernatant-rich dissolved ions of cyanide and bisulphite reused at every cycle is shown in Table 5.

As shown in Table 5, the volume of solvent required included 100, 12.5 (range 10–15) and 7.5 (range 6–9) ml for initial, second and third cycle, respectively. Therefore, the

integrated reuse would save about 60% of extraction solvent by the fourth cycle, in comparison to the traditional process.

3.1.4. E and F: Recovery

The recovery stage was aimed at eliminating the solvent-rich residues of remaining cyanide and bisulphite in a safe and economic way using a rangehood. Similarly, film solvent was

evaporated using the rangehood. This was done in order to avoid energy costs of using a separate drying method. The disposal pathway gave optimal results by consuming wastes from derivative processes and film production with zero direct emission of wastes into the environment. To minimise the energy costs associated with conventional heat drying of the biopolymers during the recovery stage, a comparative study using laminar flow hood air system and oven-heating was conducted. The comparative results between oven-drying rates and microstructural characteristics and those of laminar flow hood air system are presented in Fig. 5.

Fig. 5 shows the differences in drying rates exhibited by the two drying systems, but with similar linear decreasing curves. However, the drying rate of rangehood (curve a) is slightly faster than of oven-drying (curve b). Thus, the slightly faster drying rate of the rangehood could be an option in low-cost design processes.

The scanning electron micrographs (SEM) wastes derivatives (WD) are illustrated in Fig. 6, showing a more compact structure for a rangehood dried WD (a) and heterogeneous loose structure for oven-dried WD (b). These results imply that drying in the rangehood did not cause much alteration in the structure in contrast to the oven-drying impact, which could suggest that less physico-chemical changes occurred in the rangehood dried WD. Thus, the rangehood could be integrated in the WD design production process as a potential tool for green waste disposal.

3.1.5. G: Film package development

The purpose of integrating package development into the design was to exploit available waste derivatives, the same solvent source and a rangehood drying process. In this way, wastes to the environment are minimised and energy for solvent purification and materials drying are minimised. As a result of successful production of derivatives, flexible and transparent films with potential packaging applications were produced. The prototype films developed from the wastes and dried with the rangehood are shown in Fig. 7.

The thermal performance of the films shown by the comparisons between rangehood and oven-drying conditions is shown in Fig. 8. The thermal degradation of rangehood (a) was slightly lower than for oven-drying (b), which suggested the slow loss of volatiles. However, the degradation equalled later for both treatments. Similar behavioural patterns were observed with differential scanning calorimetric (DSC) thermograms of a and b but with lower melting temperature and sharper peak in a than b. As can be seen from the inset table, the melting (T_m) and glass transitional (T_g) temperatures were

Table 4 – Global desirability analysis of total cyanogens and showing optimal results as influenced by optimal processing conditions.

Parameter	Experimental level			Optimal derived parameter value	Properties					
					Total cyanogens, TC		D	Colour difference, ΔE		D
					Optimum	Range		Optimum	Range	
Buffer (% v/v)	0	2	4	4.0 (TC) 4.0 (ΔE)	2.0	–0.5 to 3.5	0.8	0.24	0.12 to 0.3	1.0
Waste (% w/w)	15	23	30	18.8 (TC) 22.5 (ΔE)						
Sodium bisulphite (% w/w)	1	2	3	3.0 (TC) 3.0 (ΔE)						

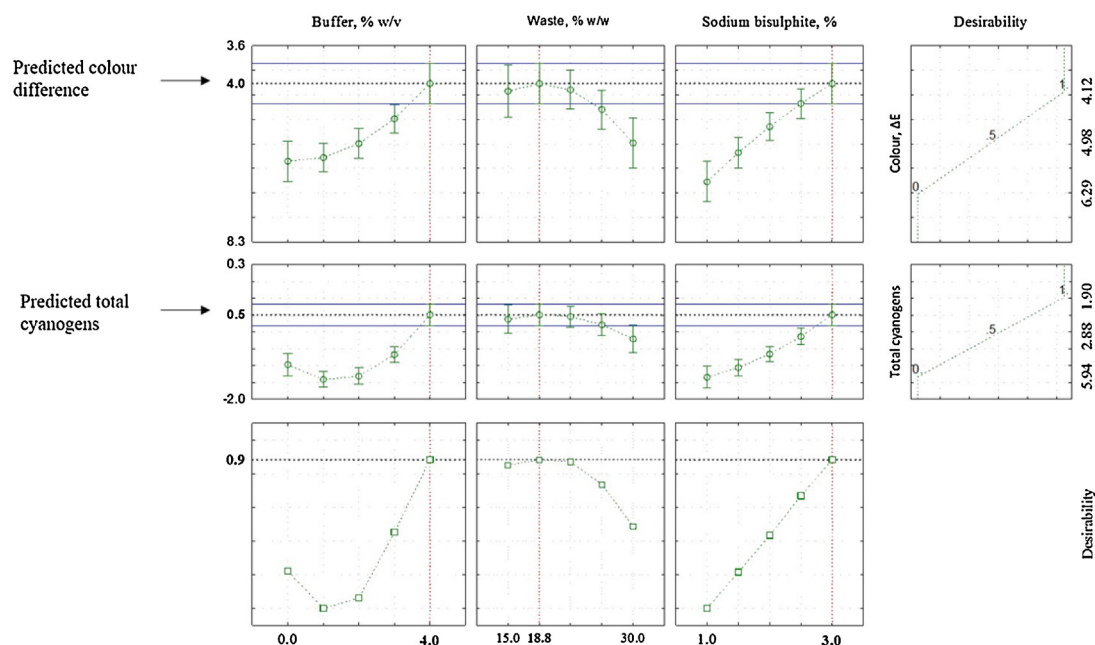


Fig. 4 – Global desirability analysis of total cyanogens and colour difference.

Table 5 – Water involved in release-recovery cycle during processing of biopolymer derivative production.

Release-recovery cycle	Volume of water/100 g pulp, ml	Supernatant reuse, ml	Solvent recovery, %
1	100	85.5 (85–90)	87.5
2	100	90.0 (88–92)	90.0
3	100	92.5 (91–94)	92.5

in the same range, in contrast to the lower crystallinity (C) of the rangehood. The high C in films dried by ovens could be due to heating that disrupted the microstructure (Denry et al., 2012).

The water vapour transmission rate (WVTR) is an important parameter for package performance and could be used to compare technologies. The film WVTR using the rangehood (707.4 g/m² day) was slightly higher than for oven-drying (685.7 g/m² day). The results show that non-heat drying process can be integrated with heat dryers to reduce energy. This could be due to a weak surface resistance of films at higher airflow velocity. Conversely, the observed value in oven dry films could be related to saturated vapour pressure of water at lower velocity.

Physical and chemical changes can be affected by many production processes including drying. Fourier transform infrared (FTIR) spectroscopy was aimed at understanding the possible structural and physico-chemical alteration differences among the rangehood and oven-dried films. As

shown in Fig. 9, the rangehood (a) and oven-dried (b) films spectra were similar, suggesting that the two drying methods did not post any differences in films chemical composition (Tumwesigye et al., 2016). These findings give light on the

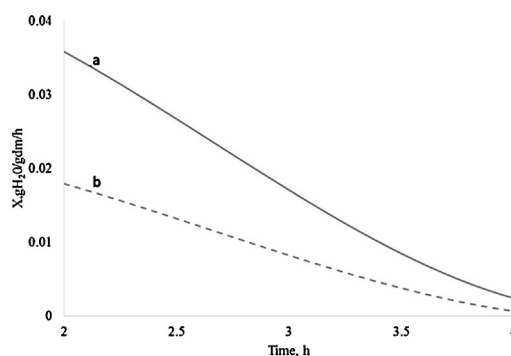


Fig. 5 – Drying rate curves of biopolymer derivatives associated with rangehood (a) and oven-drying (b).

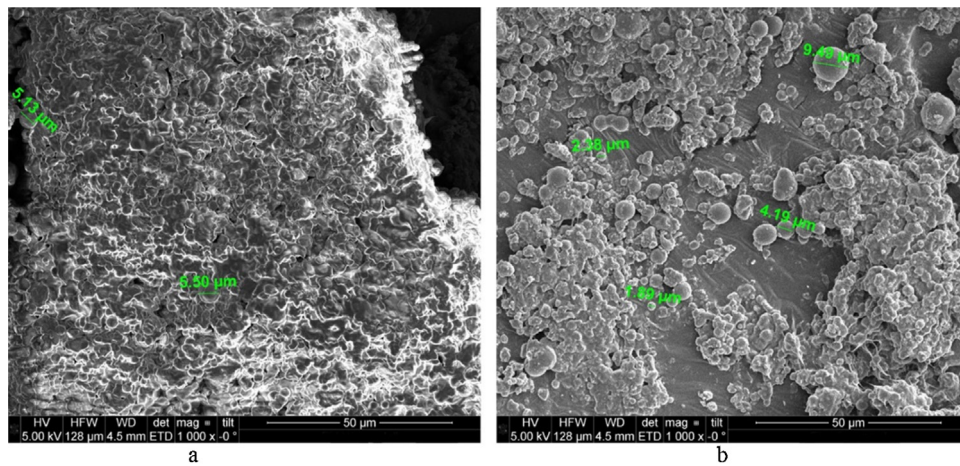


Fig. 6 – SEM microstructural characteristics of biopolymer derivatives dried using rangehood (a) and oven-drying (b).



Fig. 7 – Film prototypes dried using a rangehood, as a roll (a) and bag (b).

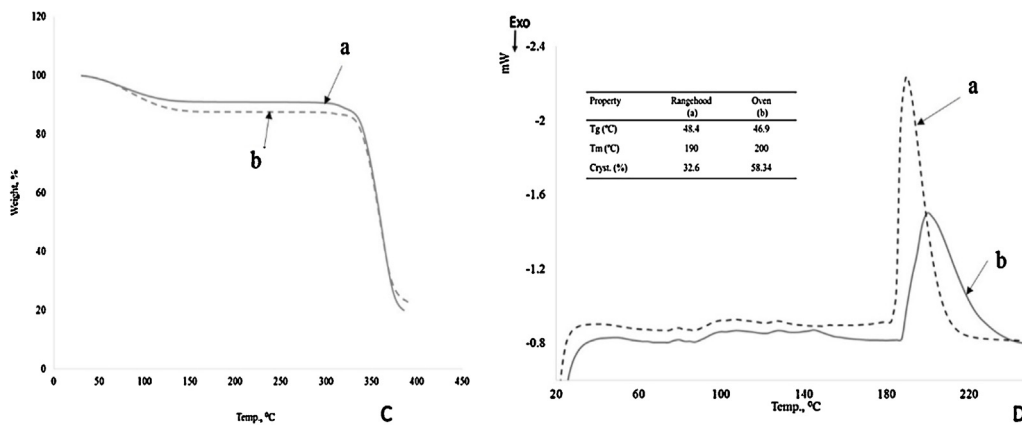


Fig. 8 – TGA degradation (C) and DSC thermograms (D) of rangehood (a) and heat oven (b) dried films.

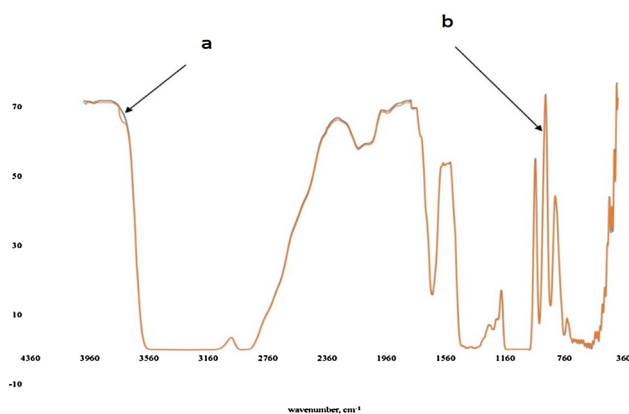


Fig. 9 – FTIR spectra of rangehood (a) and heat oven (b) dried films.

improvement of the rangehood, through optimisation of the conditions, as an alternative for integration in the design process.

4. Conclusion

This work proposed a new sustainable approach for potential utilisation of cassava waste and reduction of their environment impact using an integrated seven unit process design. The design approach is founded on the exploitation of: (i) intact (whole) cassava root; and (ii) optimised SRRC as an effective way to avoid environmental wastes accumulation, and also to reduce the energy and costs of designing additional processes for starch production, waste management and package production.

The optimised model results showed that using intact root and SRRC in biopolymer derivatives production, could be an effective tool for green cassava production processes. If ionic buffer (4%, w/v), wastes (30%, w/v), and extraction time (10 min) is applied in the process, the optimum yield could reach 45.8% which approximates the weight of the intact root. Furthermore, the integrated design process has the advantage of saving on the energy of water deionisation/distillation due to its ability to reuse wastewaters in the reactions and release processes. The analyses of drying rates and SEM for derivatives, and DSC, WVTR and FTIR for films have shown that it could be possible to substitute oven-drying with laminar flow hood air systems in the integrated design process.

Thus, the integrated design process could be used as a green tool in production of cassava products with near zero environmental waste disposal.

Acknowledgement

The research fund support provided by World Bank via NARO EAAPP project is appreciatively recognised.

References

- Adeola, F., 2011. In: Adeola, F. (Ed.), *Hazardous Wastes, Industrial Disasters, and Environmental Health Risks – Local and Global Environmental Struggles*. , 1st ed. Palgrave MacMillan/St. Martin's Press LLC, New York.
- Aripin, A.M., 2013. Cassava Peels for Alternative Fibre in Pulp and Paper Industry: Chemical Properties and Morphology Characterization. *Int. J. Intg. Eng.* 5 (1), 30–33.
- ASTM E96/E96M-05, 2005. *Standard Test Method for Water Vapor Transmission of Material*. American Society for Testing and Materials, Philadelphia.
- Bradbury, M.G., Egan, S.V., Bradbury, J.H., 1999. Determination of all forms of cyanogens in cassava roots and cassava products using picrate paper kits. *J. Sci. Food Agric.* 79 (4), 593–601.
- Cereda, M.P., Mattos, M.C.Y., 1996. Linamarin: the toxic compound of cassava. *J. Venom. Anim. Toxins* 2 (1), 6–12.
- Crowe, J., Bradshaw, T., 2014. *Chemistry for the Biosciences: The Essential Concepts*. Oxford University Press.
- Denry, I., Holloway, J.A., Gupta, P.K., 2012. Effect of crystallization heat treatment on the microstructure of niobium-doped fluorapatite glass-ceramics. *J. Biomed. Mater. Res.: Part B Appl. Biomater.* 100B (5), 1198–1205.
- Derringer, G., 1980. Simultaneous optimization of several response variables. *J. Qual. Technol.* 12, 214–219.
- Ezejiolor, T.I.N., Enebaku, U.E., Ogueke, C., 2014. Waste to wealth-value recovery from agro-food processing wastes using biotechnology: a review. *J. Br. Biotechnol.* 4 (4), 418–481.
- Guo, C., Zhou, L., Lv, J., 2013. Effects of expandable graphite and modified ammonium polyphosphate on the flame-retardant and mechanical properties of wood flour-polypropylene composites. *Polym. Polym. Compos.* 21 (7), 449–456.
- Hartert, T.V., 2007. *Bronchial asthma: a guide for practical understanding and treatment*. *Respir. Care* 52 (4), 491.
- John, R.P. (Ed.), 2009. *Biotechnology for Agro-Industrial Residues Utilisation*. Springer, pp. 225–237.
- Kolawole, O.P., 2014. Cassava processing and the environmental effect. In: *World Sustainability Forum 2014*, pp. 1–7.
- Maieves, H.A., Oliveira, D.C., De Frescura, J.R., Amante, E.R., 2011. Selection of cultivars for minimization of waste and of water consumption in cassava starch production. *Ind. Crops Prod.* 33 (1), 224–228.
- Majozi, T., Gouws, J.F., 2009. A mathematical optimisation approach for wastewater minimisation in multipurpose batch plants: multiple contaminants. *Comput. Chem. Eng.* 33 (11), 1826–1840.
- Raabe, J., Fonseca, A.D.S., Bufalino, L., Ribeiro, C., Martins, M.A., Marconcini, J.M., . . . , Tonoli, G.H.D., 2015. Biocomposite of cassava starch reinforced with cellulose pulp fibers modified with deposition of silica (SiO₂) nanoparticles. *J. Nanomater.* 2015, 1–9.
- Tumwesigye, K.S., Oliveira, J.C., Sousa-Gallagher, M.J., 2016. New sustainable approach to reduce cassava borne environmental waste and develop biodegradable materials for food packaging applications. *Food Packag. Shelf Life* 7, 8–19.
- Ubalua, A.O., 2007. Cassava wastes: treatment options and value addition alternatives. *Afr. J. Biotechnol.* 6 (18), 2065–2073.
- Versino, F., López, O.V., García, M.A., 2015. Sustainable use of cassava (*Manihot esculenta*) roots as raw material for biocomposites development. *Ind. Crops Prod.* 65, 79–89.