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Research Article

Energy Saving Process Scheme and Quality of Wheat-Cassava Spaghetti Using Fresh Cassava Substitution

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Escalating energy costs in resource-limited cassava growing regions impede industrial exploits, which contribute to high postharvest loss in the cassava value chain. Studies have uncovered potentials for replacing up to 50% of spaghetti wheat flour (WF) with cassava flour (CF) (i.e., cassava-wheat flour spaghetti (CWFS)). Modification of the CWFS scheme is proposed to eliminate the CF drying energy and explore the direct use of dewatered cassava pulp (DCP) and WF to produce spaghetti (i.e., cassava dough-wheat flour spaghetti (CDWFS)). However, uncertainties regarding the energy and product quality impacts of CDWFS compared to conventional wheat flour spaghetti (WFS) are foreseeable constraints to the industrial adoptions. Therefore, the referred impacts were analysed based on established schemes for the feedstock production (i.e., CF, WF, and DCP) and laboratory demonstrations of the spaghetti processing. All three schemes showed comparable product yields (≈0.665-0.671 kg/kg dough). Egg incorporation to augment the protein content in the CWFS and CDWFS also proved strategic for achieving comparable compositions (moisture, crude fiber, and carbohydrate), energy content, and cooking qualities (cohesiveness, adhesiveness, and water absorption) with commercial WFS products. The CWFS and CDWFS schemes could mitigate the process energy by 5.64% and 14.25%, respectively, compared to the WFS. Hence, the CWFS and CDWFS schemes are promising for energy cost reduction and advancing sustainable spaghetti industries in energy-resource-limited cassava growing regions.

1. Introduction

Pasta is one of the most popular and widely consumed food products worldwide due to its convenient form and ease to cook, long shelf life, and availability in assorted shapes and sizes [1]. Spaghetti, a cylindrical strand-shaped pasta, is the commonly preferred form [2, 3]. Spaghetti is largely made from durum wheat (*Triticum durum)* and involves the milling of wheat into semolina and mixing with water to form a dough that is extruded into the spaghetti strand shapes for drying [1, 4]. The incorporation of additional ingredients including salt, vegetable oil coloring, and egg into the spaghetti production has been reported [1, 4–6].

In recent years, the use of alternative starch sources as flour feedstock for spaghetti production has been explored, including starchy roots and tubers such as cassava (*Manihot esculenta*) [4, 6]. The cassava spaghetti exploits emerged as one of the mitigating strategies to rapid postharvest deterioration due to the lack of sustainable cassava industries to process the underutilized cassava produce [7–9]. The high moisture content of cassava (≈60-70% w/w), which is one of the reasons for the low shelf life of 2-3 days postharvest, contributes to the rapid postharvest deterioration [10]. Another contributing factor to the cassava spaghetti exploits was to reduce expenditure on large spaghetti imports to some leading cassava-growing regions [9]. For instance, pasta imports into Ghana and Brazil, the fourth and sixth global leading producers of cassava with annual capacities of 22 million and 18.2 million tonnes, respectively [11], amounted to US $35.2 million and US $31.2 million, respectively, in 2021 [3, 12].

Cassava can be classified into two varieties depending on the cyanoglycoside content, namely, the "bitter" and "sweet" varieties with the sweet type having less cyanoglycoside (<140 mg HCN/kg dry basis) than the bitter (>140 mg HCN/kg) [13]. Various process steps in the processing of cassava eliminate the cyanoglycoside as observed for the sweet and bitter varieties [14]. The cyanoglycoside is evenly distributed in the tubers of the sweet type, while it is mostly concentrated in the peels of the bitter type, thus largely eliminated via grating/pressing and peeling, respectively [13]. For instance, a 95% decrease in cyanogen concentration after grating of a sweet cassava variety has been reported [15]. Therefore, considering the toxicity of cyanide in the cyanoglycoside, its reduction to the recommended safe limits of ≤10 mg HCN/kg during the processing of the cassava is imperative for food safety requirements [16], which calls for process adaptations depending on the cassava variety. Food poisoning from the consumption of poorly processed cassava products (e.g., cassava flour) with cyanide contents above the recommended levels (≤10 mg HCN/kg) has been reported [16–18]. Conversely, a mechanized cassava flour process designed for producing high-quality cassava flour (HQCF), which involves peeling, washing, grating, pressing, drying, milling, and sifting operations, showed potentials to moderate the cyanide contents of the HQCF to acceptable levels [16, 17]. Formulation of composite flour using the HQCF and wheat flour (WF) for bakery products has been evaluated and implemented at industrial scales in some cassava-growing regions such as Nigeria [7, 9]. Thus, in order to enhance consumer safety and acceptance for industrial applications, there is a need to incorporate food safety strategies in the design of the cassava-based spaghetti processes.

Technical feasibility of the cassava-wheat flour-based spaghetti (CWFS) production process and consumer perceptions of the product qualities have been investigated and found satisfactory when compared to wheat flour-based spaghetti (WFS) [6, 19]. For instance, previous works evaluated the product qualities of different formulations of CWFS via laboratory and sensory analysis and found a blend ratio of 50 : 50% (mass basis) to be satisfactory, while HQCF-only-based spaghetti production was technically not feasible due to poor spaghetti dough properties such as high swelling power [4, 6]. One major constraint to cassava exploits as wheat replacement in culinary applications such as spaghetti production is the inability to form a viscoelastic dough like wheat flour, attributable to the lack of gluten in cassava [20]. Gluten is a protein complex found in wheat flour and comprises of gliadin and glutenin proteins which interact in the presence of water to form a network structure that binds starch granules together, thus giving wheat dough its desirable physical properties such as stretchability, cohesion, and elasticity [21]. The absence of gluten protein in cassava flour therefore accounts for its poor dough-forming property [20]. Hence, the integration with wheat flour presents an opportunity to utilizing cassava to substitute wheat flour in high-end culinary applications, thereby unlocking potentials to commercializing of underutilized cassava resource.

The total energy required to produce the HQCF and WF feedstock has been estimated at 0.038 kWh/kg and 0.252 kWh/kg, respectively [22], where the drying operations account for ≈16.4% and 5.4%, respectively [22]. Similarly, the energy consumption of a pasta-producing facility has been reported as 1.1 kWh of thermal energy and 0.18 kWh of electricity per kg of pasta produced [23]. Carlsson-Kanyama and Faist [24] found similar energy consumption values at 0.22-0.67 kWh/kg of pasta produced. Due to the energy requirements, the increasing costs and unreliability in the supply of energy (e.g., electricity and diesel fuel) in resource-limited cassava growing regions such as Nigeria, Ghana, Brazil, and Thailand impede sustainable developments in the cassava processing industries [7, 9, 25–27]. Therefore, considerations in energy reduction strategies in spaghetti process designs could be imperative to sustainable industrial expansions [7, 8].

The typical moisture contents of dewatered cassava pulp (DCP) (≈30% *w*/*w*) [17] and fresh wheat dough (≈10.9% *w*/*w*) [28] are lower than the moisture of spaghetti dough (≈40% *w*/*w*) [1, 4]. Hence, it is foreseeable that the DCP or fresh wheat dough could be directly processed into spaghetti and thereby eliminate the energy consumed in the HQCF and WF drying operations. However, uncertainties surrounding the technical feasibility, product quality, energy savings, and food safety potentials of the proposed cassava dough-wheat flour-based spaghetti (CDWFS), as compared to the proven CWFS and WFS, could pose barriers to the industrial adoption.

Therefore, to contribute to the sustainable spaghetti process designs, the present study is an early assessment work that is aimed at unraveling (i) the technical feasibility of a proposed lab-scale CDWFS scheme to inform future possibility of scaling-up for industrial applications and (ii) the energy saving potentials, food safety implications, and product qualities of the CWFS and CDWFS schemes versus the conventional WFS scheme through the use of laboratory-derived process data and first principle calculations to estimate the process energy consumptions. Thus, this study can serve as an early guidance to designing sustainable spaghetti process schemes for cassava-growing regions, as well as provide insights for implementation decision-making and sustainable industrial developments.

2. Materials and Method

2.1. Scope of the Study. This study builds on the identified feasible and consumer-accepted 50 : 50% cassava-wheat-based spaghetti [6, 19] to investigate the product quality and energy potentials of the alternate spaghetti process schemes (i.e., WFS, CWFS, and CDWFS). The product quality assessments involved analyzing and comparing the compositions and spaghetti cooking properties (water absorption and texture profile) of WFS, CWFS, and CDWFS vs. a wheat semolina-based commercial spaghetti product (CSP) as a control (Section 2.4). The energy assessment involved estimating and comparing the energy consumptions for the alternate schemes (Section 2.6).

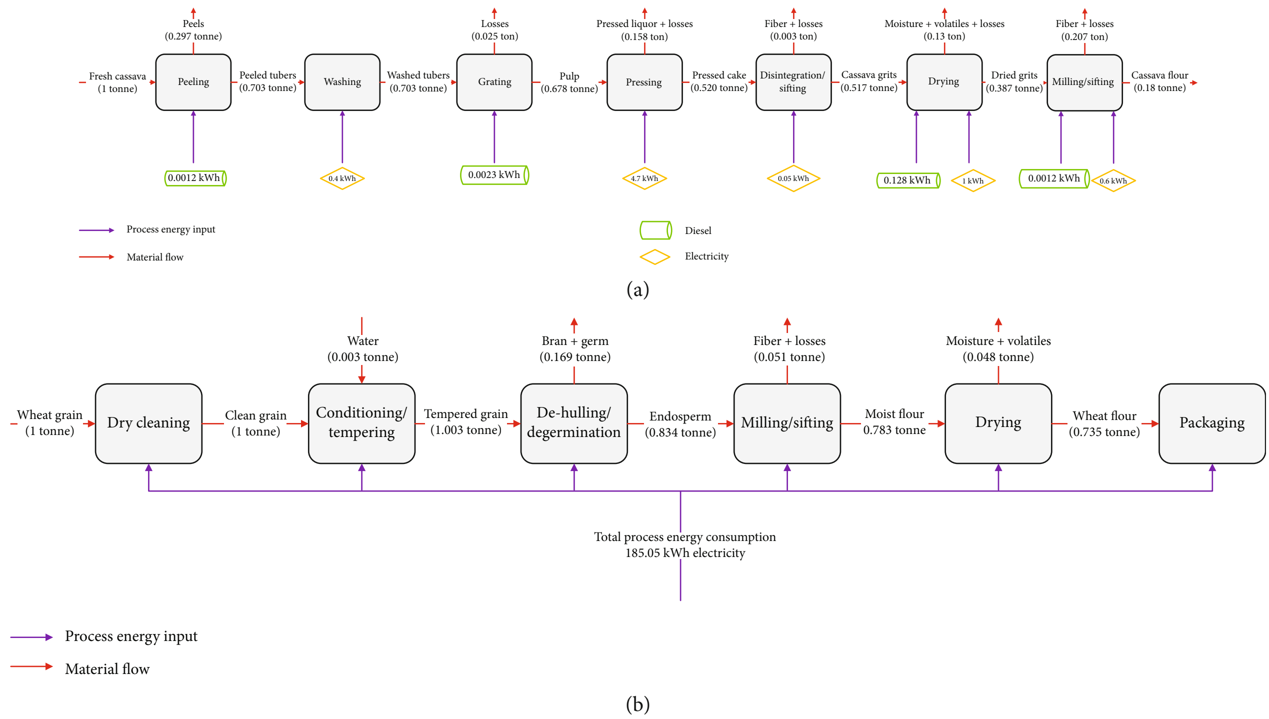

Figure 1: Block flow diagram for (a) mechanized high-quality cassava flour (HQCF) process showing the material balances and energy demands (adapted from [22]). (b) Mechanized wheat flour process showing the material and energy demands (adapted from previous work on mechanized maize flour process [22]. The material flows were adjusted for differences in grain compositions while assuming similar energy consumptions due to the similar unit operations and processing approach [31]).

2.2. Raw Materials. The cassava variety selection was based on sustainability factors including agronomic performances (e.g., high yield and disease resistance), adaptability to diverse agroecological conditions (e.g., soil and climate conditions), and low cyanide content [4, 10]. Accordingly, *Sika Bankye, a* variety of sweet cassava, was considered [29] and obtained from a commercial farmer (Bankyekrom, Ho, Ghana) and processed into HQCF at the Root and Tuber Products Development Unit (RTPDU) of Food Research Institute of the Council for Scientific and Industrial Research (CSIR-FRI), Ghana. The wheat flour was sourced from Irani Brothers and Others Ltd. (Ghana)—an industrial processor of imported durum wheat (*Triticum durum*) into flour. Table salt and egg, the additional ingredients applied to enhance the taste and dough properties (texture, nutrition, color, and spaghetti cooking behavior), respectively [4, 19], were sourced from Shoprite shopping mall, Accra, Ghana.

2.3. Spaghetti Feedstock Production and Processing Schemes

2.3.1. High-Quality Cassava Flour Process. The HQCF production at the RTPDU follows the grating scheme described by [17] (Figure 1(a)). Fresh cassava roots (12 months old) were sorted and peeled by hand, followed by thorough washing in clean water for removal of impurities (e.g., sand particles and dirt). The peeled root was grated into pulp using motorized cassava graters (Massis Ent., Tema, Ghana) to increase the surface area for easy dewatering [17, 30]. Dewatering of the pulp was done by pressing in a mechanized screw-press (Massis Ent., Tema, Ghana) for 45 min [17, 30]. The pressed cake was then disintegrated and sieved using a rotary sieve (First Products Ltd., Accra, Ghana) to reduce the fiber content [17, 30]. The sieved cassava grit was dried to a moisture of ≈12% (Apex Ltd., Model A27685, London, UK), followed by milling in a hammer mill (Carter Day International Inc., Minneapolis, MN, USA) to obtain a flour that was sifted using a 500 μm motorized flour sifter (First Products Ltd., Accra, Ghana) [17, 30]. The flour was packaged in polypropylene sacks (to prevent moisture uptake) for subsequent work.

2.3.2. Wheat Flour Process. The product yield and energy demand of the industrial mechanized WF process were assessed based on the tempering-degerming approach described in Figure 1(b) which follows the comprehensive process descriptions in the literature [22, 31, 32].

2.3.3. Wheat Flour-Based Spaghetti Production Process. The WF-based spaghetti (WFS) production process followed adapted protocols from previous works [1, 4] using the following ingredient formulation: 200 g of WF, 90 g of water, 2 g of salt, and 45 g of whisked egg (Figure 2). The dry ingredients (i.e., WF and salt) were sifted using a hand-operated 250 μm sieve (Science First Inc., Model Fieldmaster 621-7110, Yulee, FL, USA) and mixed. A portion (≈50 g) of the sifted flour was pregelatinized by the addition of 90 g of hot water (55°C) and then kneaded together with the remaining WF and salt mixture and egg to form the dough [1, 4]. The dough was allowed to rest for 15 min, after which a second kneading was performed [4]. All flour mixing and dough kneading were achieved using an electric mixer

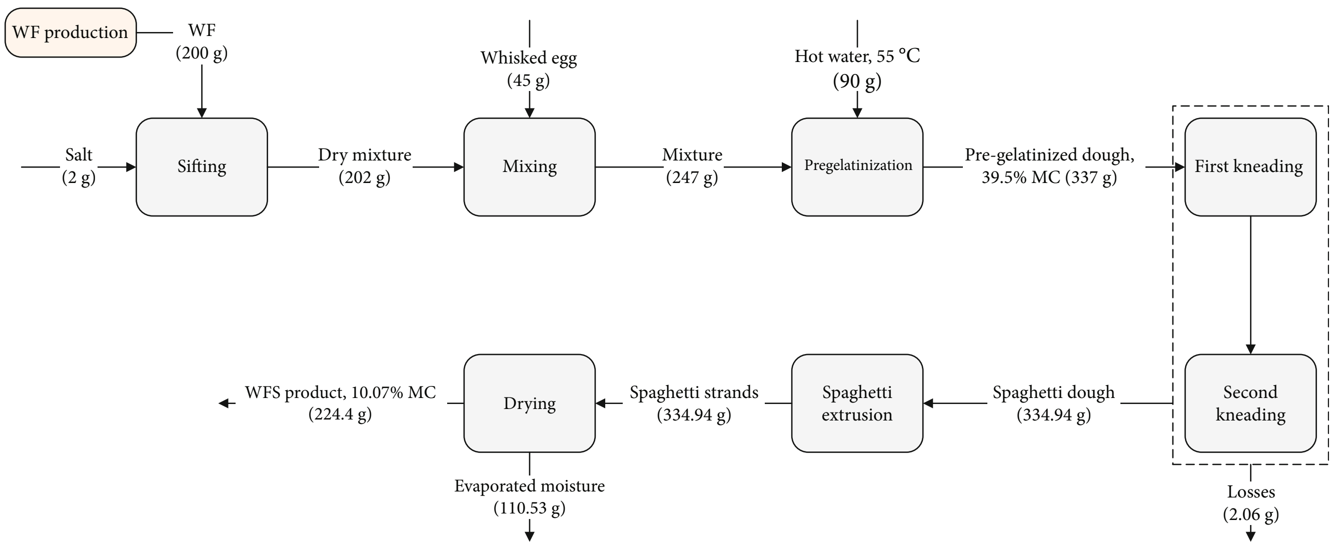

Figure 2: Block flow diagram for the experimental wheat flour-based spaghetti production scheme showing the mass balance results. WF = wheat flour; WFS = wheat flour-based spaghetti; MC = moisture content.

(Binatone, Model KM-1000, London, UK) operated at the recommended speed setting for dough processing activities (i.e., 2 on a scale of 0-8) [33]. The mixed dough was then pressed into the spaghetti strand shapes (1.5 mm diameter) by means of a hand-operated spaghetti extruder (Tagliapasta, Model TP-T02021, Molinella, Bologna, Italy). The extruded spaghetti was oven-dried at 55°C for 11 h in an electric drying oven (Binder, Model BD 115, Tuttlingen, Germany) [1]. The spaghetti samples were then allowed to cool to room temperature (≈26°C) and packaged in airtight polyethylene bags for onward analysis.

2.3.4. Cassava-Wheat Flour-Based Spaghetti Production Process. The cassava-wheat flour-based spaghetti (CWFS) production process is similar to the previously described WFS process (Section 2.3.3) except for the starting flour material that consists of WF and HQCF in 50 : 50% blend ratio (i.e., 100 g of wheat flour and 100 g of HQCF) [19] (Figure 3). Prior to the application in the process, the composite flour was uniformly blended via sifting and mixing using the 250 μm mesh sieve and the electric mixer, respectively.

2.3.5. Cassava Dough-Wheat Flour-Based Spaghetti Production Process. The proposed CDWFS process (Section 1) is a modification of the CWFS process in Section 2.3.4, which was aimed at eliminating the energy-intensive drying unit operation of the HQCF process from the spaghetti processing. The process involved the processing of the cassava roots into DCP for direct application in the spaghetti production process (Figure 4). The DCP process is similar to the grating scheme HQCF process but ends at the pressed cake disintegration and sifting stage (see Section 2.3.1). The moisture content of the disintegrated dough (≈30%) was then adjusted to ≈48% (i.e., correspond to 90 g of water:100 g of dry DCP) via the addition of hot water (55°C) and pregelatinized. The 190 g of pregelatinized dough was then kneaded with the previously sifted and mixed 100 g of WF, 2 g of salt, and 45 g of whisked egg for the spaghetti production following similar steps as the CWFS process in Section 2.3.4.

2.4. Product Quality Assessment

2.4.1. Composition Analysis. The proximate compositions of the spaghetti products (WFS, CWFS, and CDWFS) and the CSP were determined according to the methods described in AOAC [34, 35]. Specifically, the moisture, ash, total fat, protein, and total dietary fiber (TDF) were determined following the AOAC methods 32.1.03, 32.1.05, 4.5.01, 4.2.09, and 985.29, respectively [34, 35]. Total carbohydrate was determined by the difference method (Equation (1)) [36]. The energy content was calculated based on the Atwater conversion factors (Equation (2)) [37]. The sodium content was evaluated according to the AOAC method 937.09 [34, 38]. The cyanide contents of the uncooked and cooked CWFS and CDWFS products were analyzed as hydrogen cyanide (HCN) equivalents following the AOAC method 49.11.02 [34, 35].

$$\%\text{carbohydrate} = 100 - (\%\text{moisture} + \%\text{protein} + \%\text{crude fiber} + \%\text{fat} + \%\text{ash}), \quad (1)$$

$$\text{Energy (in kcal/100g)} = (9 \times \%\text{fat}) + (4 \times \%\text{protein}) + (4 \times \%\text{carbohydrate}). \quad (2)$$

2.4.2. Spaghetti Cooking Quality

(1) Water Absorption Index. The spaghetti products and the CSP were cooked in boiling distilled water for 7 min [39]. The water absorption index (WAI), an indicator of the spaghetti's water retention ability during cooking, was determined according to Equation (3) [39].

$$\text{WAI} = \frac{W_{us} - W_{us}}{W_{us}} \times 100, \quad (3)$$

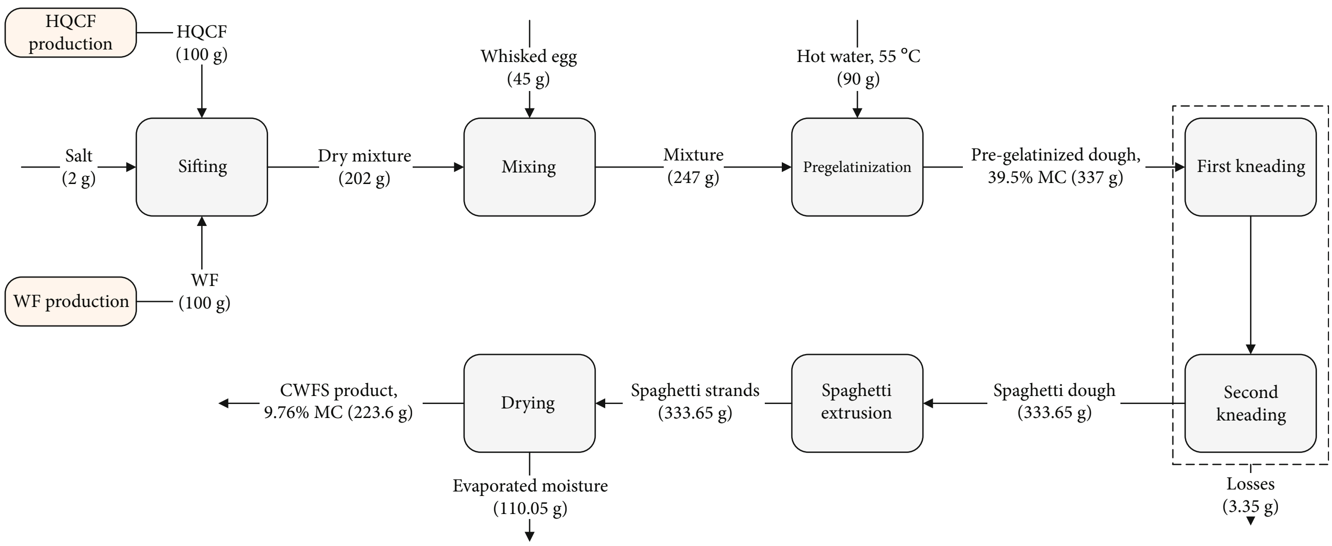

Figure 3: Block flow diagram for the experimental cassava-wheat flour-based spaghetti production scheme showing the mass balance results. WF = wheat flour; HQCF = high-quality cassava flour; CWFS = cassava-wheat flour-based spaghetti; MC = moisture content

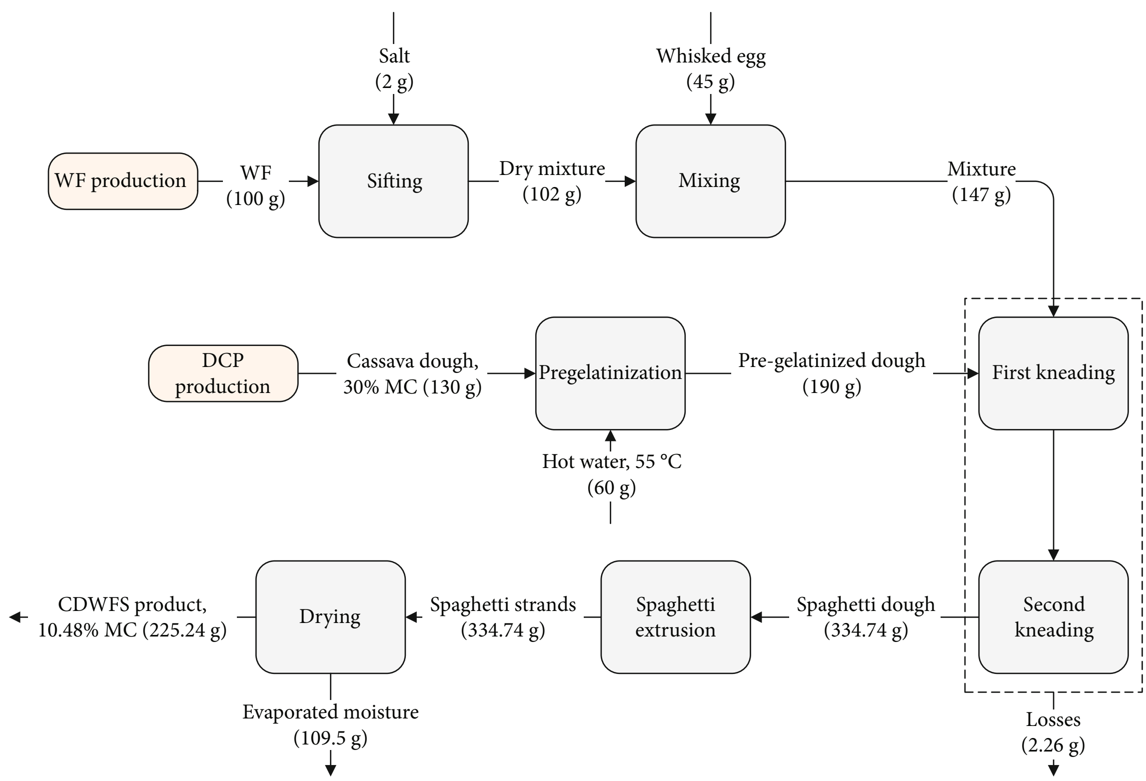

Figure 4: Block flow diagram for the experimental cassava dough-wheat flour-based spaghetti production scheme showing the mass balance results. WF = wheat flour; DCP = dewatered cassava pulp; CDWFS = cassava dough-wheat flour spaghetti; MC = moisture content

where WAI is the water absorption index, W_{cs} is the weight of cooked spaghetti (g), and W_{us} is the weight of uncooked spaghetti (g).

(2) Texture Profile Analysis. Texture profile analysis (TPA) (i.e., cohesiveness, hardness, and adhesiveness) of the cooked spaghetti products and the CSP were performed using a CT3 Texture Analyzer equipped with a 10 kg load cell (AMETEK Brookfield, MA, USA). The samples were prepared according to the AACC method 66-50.01 [40]. In the analysis, a single spaghetti sheet was compressed using a clear acrylic cylinder probe (25.4 mm diameter, 35 mm long) at a constant deformation rate of 1 mm/s until 80% of the initial thickness was attained [39]. The analysis was performed at the recommended trigger force of 10 g_f for the load cell applied (AMETEK Brookfield, MA, USA).

Table 1: Time durations for the main unit operations to process 337 g of dough into spaghetti.

Spaghetti process scheme	Process time duration for processing of 337 g dough into spaghetti (min) [1]						
	Flour+salt sifting[2]	Flour+salt+egg mixing	Pregelatinization	First kneading	Second kneading	Spaghetti extrusion[3]	Spaghetti drying[4]
WFS	4.0 ± 0.15^{a}	4.9 ± 0.85^{a}	3.2 ± 0.75^{a}	4.6 ± 1.44^{a}	5.1 ± 1.01^{a}	30.5 ± 1.6^{a}	660.0 ± 00^{a}
CWFS	7.0 ± 0.50^{b}	5.5 ± 0.45^{a}	3.8 ± 0.74^{a}	5.9 ± 1.64^{a}	4.0 ± 0.70^{a}	$27.4 \pm 3.18^{a,b}$	660.0 ± 00^{a}
CDWFS[5]	3.4 ± 0.53^{a}	3.9 ± 0.64^{a}	5.0 ± 1.00^{a}	6.3 ± 0.80^{a}	5.1 ± 1.05^{a}	21.6 ± 2.69^{b}	660.0 ± 00^{a}

[1]Values reported are mean ± standard deviation (SD) for three replications for each spaghetti process scheme and were based on visual inspection and dough feel [43]. Different letters in the same column imply the means are statistically significantly different ($p < .05$). [2]The manual sifting was performed by 1 operator. [3]The manual spaghetti extrusion was performed by 1 operator. [4]To ensure equal basis for the comparative product moisture assessment for the alternate spaghetti schemes, the drying time (using Binder BD 115 oven) was set to 11 h at 55°C [1]. [5]The reported values for the "flour+salt sifting" and "flour+salt+egg mixing" are on a basis of 200 g of WF to facilitate comparison amongst the different schemes. Thus, in the energy estimations for the CDWFS scheme, the referred values were halved to correspond the actual 100 g of WF processed in the referred operations (see Figure 4). WFS = wheat flour-based spaghetti; CWFS = cassava flour-wheat flour-based spaghetti; CDWFS = cassava dough-wheat flour-based spaghetti.

2.5. Statistical Analysis. The laboratory experiments for each spaghetti scheme were replicated three times. Thus, all the results were reported as mean plus standard deviations, and the statistically significant differences amongst the mean values for the various schemes were analyzed using a one-way analysis of variance (ANOVA), which was performed in IBM® SPSS® statistics software v.20 (IBM SPSS Inc., Cary, NC, USA). In the cases where significant differences were observed within the data, a Tukey post hoc test for multiple comparison was performed to determine which specific mean values were significantly different ($p < .05$).

2.6. Process Energy Estimations. To analyze the energy performances of the spaghetti processes (i.e., WFS, CWFS, and CDWFS), the process energy consumption per unit of spaghetti produced (i.e., kWh/kg of spaghetti) termed energy intensity [41] was evaluated and compared. The evaluation approach involved estimating and adding the energy intensities for the feedstock (i.e., HQCF, WF, and DCP) production process (E_{fprod}) and the processing of the feedstock into spaghetti (E_{fproc}) (Equation (4)). The E_{fprod} for the HQCF, WF, and DCP feedstocks have been estimated to be 0.038 kWh/kg HQCF, 0.252 kWh/kg WF, and 0.032 kWh/kg DCP, respectively (detailed in Figures 1(a) and 1(b)) [22]. The E_{fproc} was estimated as the sum of the thermal energy (i.e., hot water and spaghetti drying, Sections 2.3.3–2.3.5), manual energy (i.e., flour sifting and extrusion operations, Sections 2.3.3–2.3.5), and electrical energy inputs (i.e., mixing, pregelatinizing, and kneading operations, Sections 2.3.3–2.3.5) to the main unit operations in the feedstock conversion process (see Figures 2–4). Thus, the assessment follows the protocols of Jekayinfa and Bamgboye [41], wherein process data (e.g., product moisture contents and operating time) from the laboratory demonstrations are applied to calculate the process energy consumptions as shown in Equations (5)–(8). In the electrical energy assessment (Equation (8)), the specification sheet power rating of 0.25 kW (correspond to speed of 2 on a scale of 0-8) for the Binatone KM-1000 multipurpose mixer was applied [33, 42]. Table 1 presents the applied time durations for the unit operations (Equations (7) and (8)) which were identified based on visual inspection and dough feel [43]. The spaghetti drying protocol was aimed at achieving the critical moisture content of the product to obviate microbial activities in the product [44]. Thus, the energy required to dry the extruded spaghetti to the achieved moisture contents for the 11 h drying period (Tables 1 and 2) was considered (see Equation (6)).

$$E_{\text{total}} = E_{\text{fprod}} + E_{\text{fproc}}, \tag{4}$$

$$E_{\text{fproc}} = E_{\text{thermal}} + E_{\text{manual}} + E_{\text{elec}}, \tag{5}$$

$$E_{\text{thermal}} = \frac{M_w C_w \left(T_{wf} - T_{wi}\right) + M_d C_d \left(T_{sf} - T_{si}\right) + M_e \lambda_w}{3600 M_s}, \tag{6}$$

$$E_{\text{manual}} = \frac{0.075\text{Nt}}{M_s}, \tag{7}$$

$$E_{\text{elec}} = \frac{Pt}{M_s}, \tag{8}$$

where E_{total} is the total energy intensity of the spaghetti production process (kWh/kg spaghetti), E_{fprod} is the energy intensity of the feedstock production process (estimated to be 0.038 kWh/kg of HQCF, 0.252 kWh/kg of WF, and 0.032 kWh/kg of DCP [22]), E_{fproc} is the energy intensity of the process converting the feedstock into spaghetti (kWh/kg spaghetti), E_{thermal} is the specific energy content of the 55°C of hot water applied in the spaghetti process plus the energy intensity of the spaghetti drying operation (kWh/kg spaghetti), M_w is the mass of hot water applied in the spaghetti process (kg), C_w is the specific heat capacity of water (4.187 kJ/kg.°C), T_{wf} and T_{wi} are the final (55°C) and initial temperatures (25°C) of the heated water, respectively, M_d is the mass of the spaghetti before drying (kg), C_d is the specific heat capacity of the spaghetti dough (adopted value of 2.8 kJ/kg.°C for dough with 42% moisture and at 21°C [45]), T_{sf} and T_{si} are the final (100°C) and initial temperatures (30°C) of the dried spaghetti, respectively, M_e is the mass of moisture evaporated from the spaghetti (kg) (see Figures 2–4), λ_w is the latent heat of vaporization of water at 100°C (2257 kJ/kg), 3600 is the conversion factor from kJ to kWh, M_s is the total mass of the spaghetti produced (kg spaghetti), E_{manual} is the energy intensity of the manual flour sifting and dough extrusion operations in the spaghetti

Table 2: Proximate compositions, cyanide, and sodium contents of the various spaghetti products.

Components	WFS	CWFS	CDWFS	CSP
	Proximate composition (g/100 g)[1]			
Moisture	10.1 ± 0.02[a,b]	9.7 ± 0.00[a]	10.5 ± 0.07[a,b]	8.4 ± 0.28[c]
Ash	1.2 ± 0.02[a]	1.4 ± 0.01[b]	2.0 ± 0.02[c]	1.9 ± 0.04[d]
Total fat	2.6 ± 0.07[a]	6.7 ± 0.01[b]	4.6 ± 0.01[c]	1.5 ± 0.04[d]
Protein	15.1 ± 0.13[a]	8.2 ± 0.09[b]	12.1 ± 0.08[c]	11.5 ± 0.03[d]
Crude fiber	0.2 ± 0.04[a]	0.3 ± 0.03[a]	0.5 ± 0.07[a]	2.8 ± 0.18[b]
Total carbohydrate	70.8 ± 0.05[a]	73.8 ± 0.18[b]	70.3 ± 0.08[c]	73.9 ± 0.14[b]
Energy (kcal/100 g)	367.1 ± 0.35[a]	388.0 ± 0.01[b]	371.2 ± 0.69[a]	362.0 ± 5.66[a]
	Sodium content (mg/100 g)[1]			
Sodium	4.31 ± 0.02[a]	5.44 ± 0.03[b]	4.65 ± 0.01[c]	5.10 ± 0.14[d]
	Cyanide content (mg HCN/kg)[1]			
Cyanide (uncooked spaghetti)	—	4.3 ± 0.09	5.5 ± 0.14	—
Cyanide (cooked spaghetti)	—	3.2 ± 0.07	1.9 ± 0.09	—

[1]Values reported are mean values ± standard deviation (SD) for three replications for each spaghetti product. Means with different superscript letters within the same row are significantly different ($p < .05$). WFS = wheat flour-based spaghetti; CWFS = cassava flour-wheat flour-based spaghetti; CDWFS = cassava dough-wheat flour-based spaghetti; CSP = wheat semolina-based commercial spaghetti product.

process (kWh/kg spaghetti), 0.075 is the average power of adult human labor (kW), N is the number of personnel involved in the process activity, t is the time for accomplishing the given process activity (h), E_{elec} is the electrical energy intensity for the process converting the feedstock into spaghetti (kWh/kg spaghetti), and P is the power rating of the mixer's motor (kW).

3. Results and Discussion

3.1. Technical Feasibility. The substitution of 50% of WF feedstock with the HQCF or DCP has no impact on the yield of spaghetti. Feasibility of the spaghetti processes is depicted by the visuals of the uncooked and cooked products in Figure 5. The results (Figures 5(a)–5(h)), in addition to corroborating the technical feasibility for the CWFS process [6, 19], demonstrate the technical viability of the proposed CDWFS scheme. The spaghetti production schemes (WFS, CWFS, and CDWFS) resulted in comparable product yields at ≈224-226 g of spaghetti per 337 g of dough processed (i.e., ≈0.665-0.671 kg of spaghetti/kg dough) (Figures 2–4).

3.2. Product Quality Implications

3.2.1. Product Compositions. Although the proximate analysis of the spaghetti products had considerable differences in their compositions compared to the wheat semolina-based products (CSP) (Table 2), the values are within acceptable ranges for commercial spaghetti products. For instance, the moisture contents for the WF, CWFS, and CDWFS products (9.7-10.5%) were significantly higher compared to the CSP (8.4%) (Table 2). Moisture contents ranging up to 12.4% have been reported for commercial spaghetti products [1, 46]. Several factors may explain the observed differences in the moisture, including the combined effects of the different fiber contents (Table 2) and their water retention capacities [39], as well as the differences in wheat gluten protein contents and networks that impede water diffusion across the spaghetti matrix [5]. Similarly, the comparable crude fiber contents for the three spaghetti products were significantly lower compared to the CSP (0.2-0.5% vs. 2.8%) (Table 2) but fall within reported ranges for commercial spaghetti products (≥0.003%) [46]. Compared to the WFS and CWFS, the relatively high fiber content of the CDWFS (0.2-0.3% vs. 0.5%, Table 2) could be attributed to the excess fiber from the DCP as only the WF feedstock was sifted in the spaghetti process (Table 1). Consumer interest and preference for fiber-enriched spaghetti is on the rise in recent years due to the accompanying health benefits [47, 48]. For instance, due to its resistance to digestion and absorption, dietary fiber provides a functional effect to the gastrointestinal tract and lowers the risk for developing hypertension, diabetes, obesity, and heart diseases [47, 49]. A study by Laureati et al. [47] reported positive consumer responses regarding sensory attributes for spaghetti enriched with up to 20% wheat bran fiber and negative responses for bran contents above 25%. Thus, the relatively low fiber contents obtained for the analyzed spaghetti products in this study (0.2-0.5%, Table 2) may be acceptable to consumers.

The ash, total fat, protein, and carbohydrate contents varied for the products and the CSP (Table 2). This may be attributed to the differences in feedstock compositions and the added egg ingredient for the WFS, CWFS, and CDWFS (Figures 2–4). It is worth mentioning that the wheat semolina-based CSP had no egg ingredient. Feedstock with protein contents ≥ 13% have been found to be ideal for spaghetti products with satisfactory cooking quality and the contrary for feedstock with <11% protein contents [1]. The protein composition of the *Sika Bankye* cassava is relatively low compared to durum wheat (i.e., 1.6 vs. 13.6%, respectively) [1, 29], thus the egg protein incorporation which contributed to the comparable protein contents of the CWFS and CDWFS (8.2-12.1%) vs. the WFS and CSP (11.5-15.1%) (Table 2).

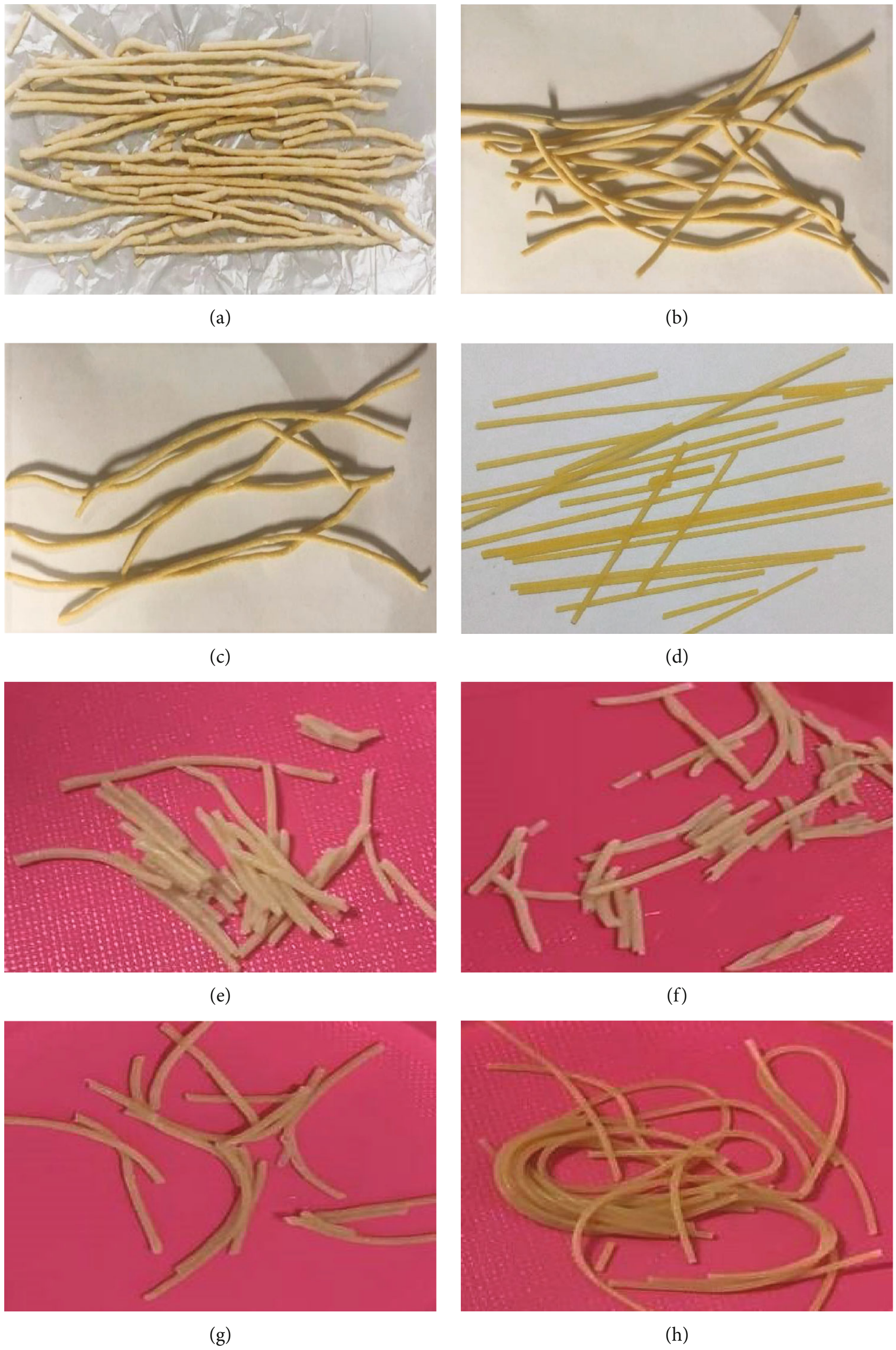

Figure 5: Images of the various spaghetti products showing. The uncooked spaghetti produced from (a) wheat flour, (b) 50% cassava-50% wheat flour feedstock, (c) 50% cassava dough-50% wheat flour feedstock, and (d) uncooked wheat semolina-based commercial spaghetti product. The cooked spaghetti produced from (e) wheat flour, (f) 50% cassava-50% wheat flour feedstock, (g) 50% cassava dough-50% wheat flour feedstock, and (h) cooked wheat semolina-based commercial spaghetti product.

The sodium content for the WFS, CWFS, and CDWFS was significantly different (Table 2). Moreover, all the three referred schemes had significantly different sodium contents vs. the CSP (4.31-5.44 vs. 5.10 mg/100 g) ($p < .05$) (Table 2). This may be attributed to the added table salt (Sections 2.3.3–2.3.5), and the differences in the sodium contents of the different feedstocks applied. According to the nutritional factsheet for CSP, no salt was applied in the production process. Sodium content of the *Sika Bankye* and the durum wheat feedstock have been estimated to be 0.32 mg/100 g and 1-5 mg/100 g, respectively [29, 50], which could explain the CSP's value of 5.1 mg/

Table 3: Texture profile analysis and water absorption index for the various spaghetti products.

	Hardness (N)[1]	Cohesiveness[1]	Adhesiveness (Nm × 10^{-4})[1]	WAI (g/100 g uncooked spaghetti)[1]
WFS	71.00 ± 8.05^{a}	0.42 ± 0.33^{a}	1.67 ± 1.53^{a}	168.9 ± 18.19^{a}
CWFS	$65.33 \pm 4.51^{a,b}$	0.51 ± 0.20^{a}	1.67 ± 2.08^{a}	$144.1 \pm 15.36^{a,b}$
CDWFS	53.17 ± 3.55^{b}	0.71 ± 0.08^{a}	2.00 ± 2.65^{a}	$104.2 \pm 3.97^{b,c}$
CSP	106.00 ± 7.81^{c}	0.57 ± 0.38^{a}	6.67 ± 8.33^{a}	$131.4 \pm 18.71^{a,c}$

[1]Values reported are mean values ± standard deviation (SD) for three replications for each spaghetti product. Means with different superscript letters within the same column are significantly different ($p < .05$). WAI = water absorption index; WFS = wheat flour-based spaghetti; CWFS = cassava flour-wheat flour-based spaghetti; CDWFS = cassava dough-wheat flour-based spaghetti; CSP = wheat semolina-based commercial spaghetti product.

100 g (Table 2). Nevertheless, the obtained sodium ranges for the investigated schemes (4.31-5.44 mg/100 g) may be acceptable when compared to reported values for commercial spaghetti products (≤5 mg/100 g) [46].

The CWFS and CDWFS schemes, together with the *Sika Bankye* cassava variety, yielded spaghetti products with safe cyanide limits. The cyanide content of the CWFS (4.3 mg HCN/kg) and CDWFS (5.5 mg HCN/kg) (Table 2) is well within the recommended safe limits of ≤10 mg HCN/kg for cassava food products [16], which could further reduce to 3.2 and 1.9 mg HCN/kg for the corresponding cooked products (Table 2). Impacts of the cassava variety and processing method on the product cyanide levels are well documented [9, 51] with the HQCF and DCP processing approach found favorable [51, 52]. The *Sika Bankye* variety is one of the common improved sweet cassava varieties with low cyanide contents that could reach 0.12 mg HCN/kg [9, 29], thus possibilities to further mitigate the health concerns when the low cyanide varieties are applied.

3.2.2. Cooked Spaghetti Qualities. The CSP was found to be significantly harder compared to the investigated spaghetti products (i.e., WFS, CWFS, and CDWFS) (106 vs. 53-71 N, Table 3), which indicates potentials for lower optimal cooking time for the investigated products [39]. The hardness for the WFS (71 N, Table 3) compares favorably to a report of 67.98 N for a similar durum wheat flour-based spaghetti [39]. Compared to the conventional WFS scheme, the incorporation of DCP into the CDWFS scheme significantly lowers the product hardness (Table 3). The hardness of the WFS, CDWFS, and CSP were significantly different, while that of the CWFS was statistically similar to the WFS ($p = .663$) or CDWFS ($p = .170$) (Table 3). Conversely, the hardness of the CDWFS was significantly lower compared to the WFS (53.17 vs. 71 N) ($p = .033$) (Table 3). The hardness of spaghetti products has been attributed to the degree of the intermolecular interactions in the spaghetti matrix [53].

Thus, stronger intermolecular interactions exist within the WFS and CWFS matrices compared to the CDWFS matrix. The hardness of spaghetti has been found to correlate negatively with the cooking mass loss, attributable to the slow disintegration due to the relatively slow migration of water to the core of a harder spaghetti [48, 54]. Thus, compared to the WFS and CWFS, high cooking loss could be projected for the CDWFS due to its lower hardness. However, the lower hardness could imply potentials for lower optimal cooking time [39] and thus beneficial regarding cooking energy saving.

The incorporation of the cassava feedstock (HQCF, DCP) into the WF-based spaghetti production had no significant ($p < 0.05$) impact on the compactness and texture of the cooked product compared to the CSP, which may imply promises for consumer acceptance [6, 39]. With respect to the cohesiveness, which is a measure of the compactness of the cooked spaghetti [39], no significant differences ($p < 0.05$) were observed amongst the spaghetti products (Table 3). Likewise, the adhesiveness, which is an indicator of the strength between the spaghetti and the contact surface [39], showed no significant differences amongst the spaghetti products analyzed (Table 3). The WAI revealed the WFS, CWFS, CDWFS, and CSP can increase in weight by ≈1.7-fold, 1.4-fold, 1.0-fold, and 1.3-fold, respectively, during cooking (Table 3). The WAI for the WFS, CWFS, and CSP were statistically ($p < 0.05$) similar (≈131-169 g/100 g uncooked spaghetti, Table 3), while the CDWFS had a lower value which was only comparable with the CSP (104 vs. 131 g/100 g, Table 3). The differences in the WAI could be attributed to the differences in the swelling power of the cassava starch molecules vs. the wheat starch molecules [4], the dissimilar wheat gluten protein contents and networks that inhibit water diffusion into starch granules [5], and the different soluble fiber contents that contribute to the water-binding capacities of the products [39].

3.3. Energy Performances. The proposed CWFS and CDWFS schemes show promises regarding energy savings compared to the prevalent WFS, which could be exploited to enhance the cost-effectiveness of the spaghetti industries in cassava-growing regions. The total process energy consumptions for the processing of the 337 g of dough into the WFS, CWFS, and CDWFS were estimated to be 0.259, 0.243, and 0.223 kWh, respectively (Figure 6(a)). These translate into energy intensities of ≈1.15, 1.09, and 0.99 kWh/kg of spaghetti produced, respectively (Figure 6(b)), which compare fairly with findings for a pasta processing facility (≈1.28 kWh/kg) [23]. Hence, compared to the WFS scheme, the CWFS and CDWFS schemes could potentially mitigate the process energy by 5.64% and 14.25%, respectively (Figure 6(b)). Thus, the CWFS and CDWFS schemes could potentially promote energy cost reductions that will impact positively on the profitability of the spaghetti industries.

Processing of the WF, HQCF, and DCP feedstocks into spaghetti represents the dominant energy-consuming

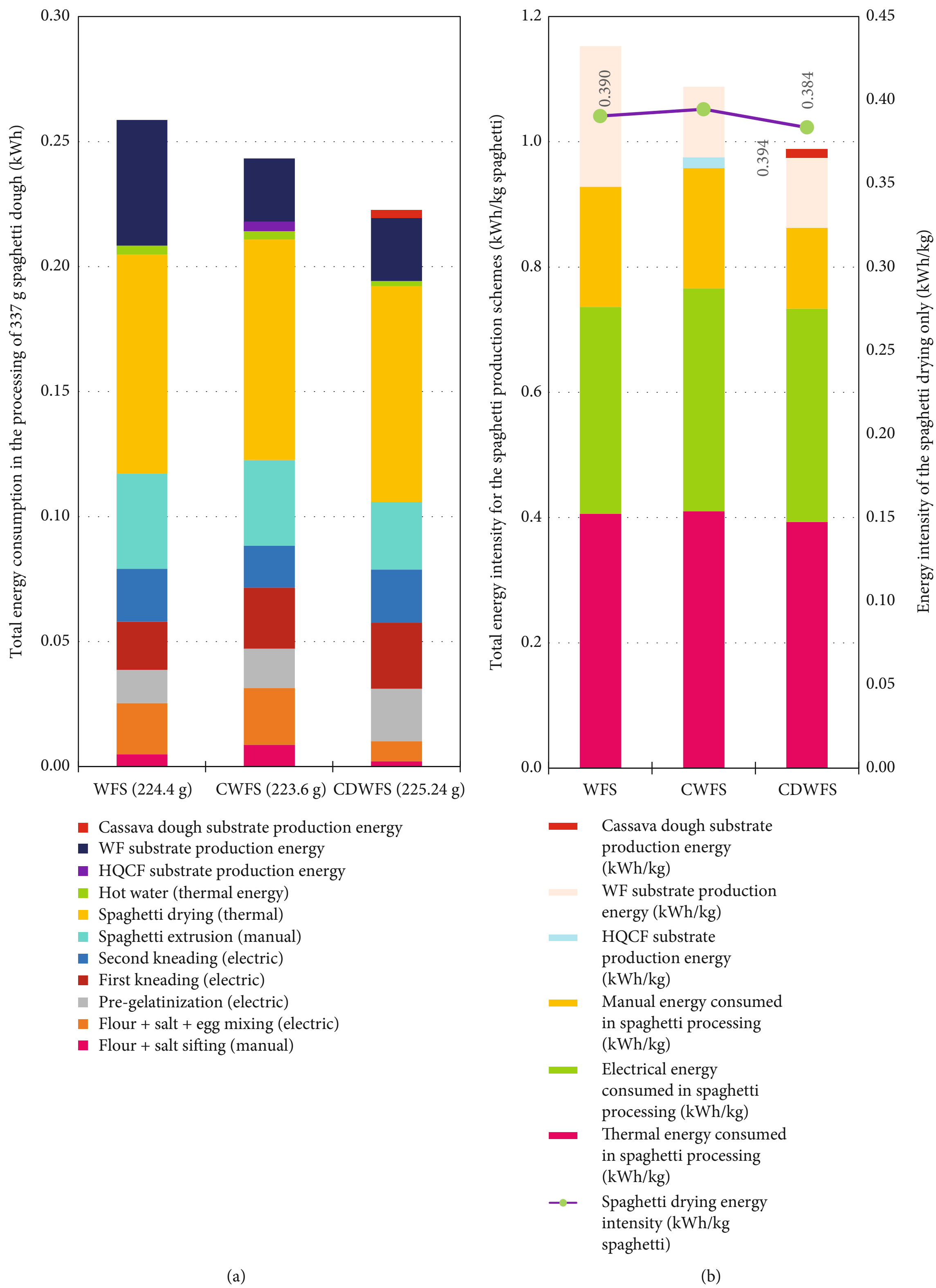

Figure 6: (a) Total energy consumption estimates for the various spaghetti production schemes. (b) Energy intensity estimates for the considered spaghetti schemes. WFS = wheat flour-based spaghetti; CWFS = cassava-wheat flour-based spaghetti; CDWFS = cassava dough-wheat flour-based spaghetti.

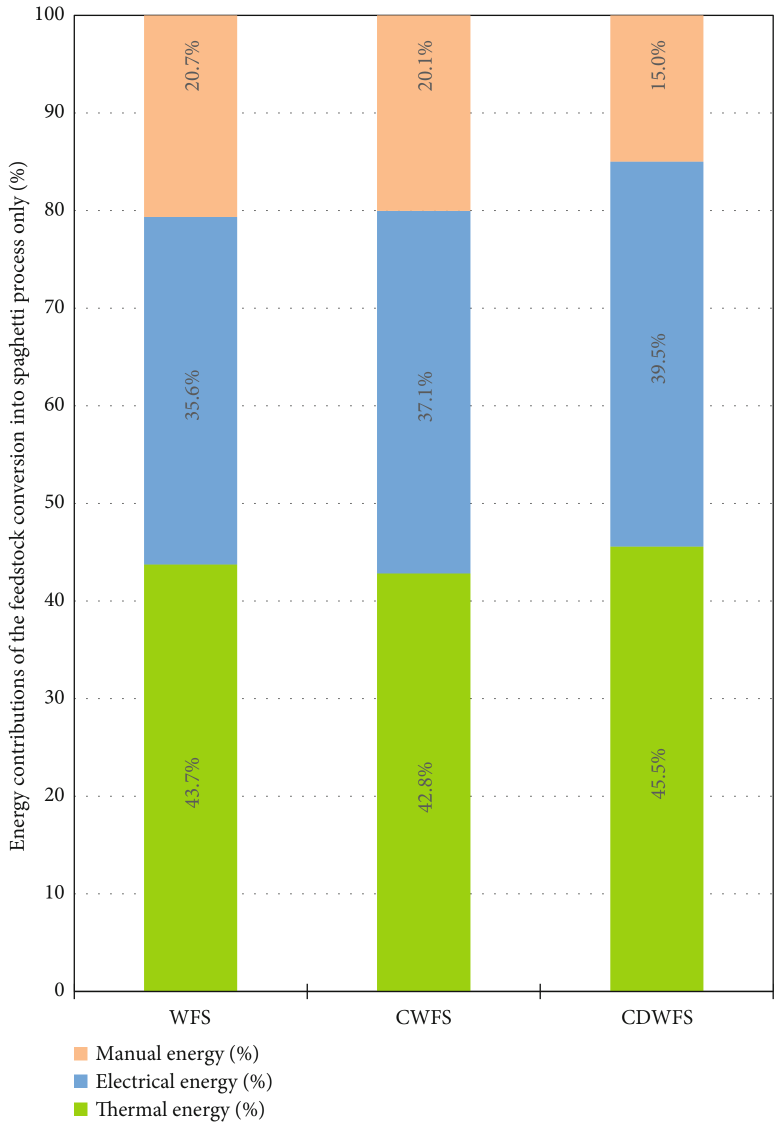

Figure 7: Percentage contributions of the energy forms to the energy demands in processing of the feedstock into spaghetti. WFS = wheat flour-based spaghetti; CWFS = cassava-wheat flour-based spaghetti; CDWFS = cassava dough-wheat-flour based spaghetti.

section for the analyzed spaghetti schemes, accounting for 80.54% (WFS), 88.08% (CWFS), and 87.26% (CDWFS) of the total energy demands (Figures 6(a) and 6(b)). Nevertheless, the energy contributions from the WF, HQCF, and DCP feedstock production sections are notable at 11.92-19.46% (Figures 6(a) and 6(b)), thus underscores the need for exploring less energy-intensive options. To this end, the proposed use of cassava as 50% wheat flour substitute in spaghetti production [19] may be apt considering the lower energy intensity estimate for HQCF vs. WF (i.e., 0.038 kWh/kg HQCF vs. 0.252 kWh/kg of WF) (Figures 1(a) and 1(b)) [22]. A similar energy trend has been reported for corresponding starch production processes (i.e., 0.166 kWh/kg of cassava starch [55] vs. 1.40 kWh/kg of wheat starch [31]).

With respect to the energy consumption of the feedstock processing section, the thermal energy (i.e., hot water and spaghetti drying) accounts for ≈42.8-45.5% (Figure 7), which can be compared to a report of 85% for an industrial pasta facility when the difference in the dryer efficiency is considered [23]. In relation to the whole process (i.e., conversion of the crops into feedstock, then into spaghetti), the spaghetti drying operation represents the energy hotspot (i.e., 33.9-38.8% of the total, Figure 6(a)). The manual energy intensity estimates for the spaghetti extrusion at 0.17 kWh/kg (WFS), 0.15 kWh/kg (CWFS), and 0.12 kWh/kg (CDWFS) (Figure 6(a)) compare equitably with reports for electrical powered spaghetti extrusion operations (0.07-0.13 kWh/kg) [56]. Wójtowicz and MoĞcicki [56], through experimental investigations using a mechanized extruder, found that the energy intensity of the spaghetti extrusion operation decreases with increasing moisture content and temperature of the dough. Therefore, the relatively high moisture content of the CDWFS (10.5%) vs. the WFS (10.1%) and CWFS (9.7%) (Table 2) may have contributed to the relatively low extrusion energy estimate for the CDWFS (Figure 6(a)). Hence, the manual energy estimates for the extrusion operation may be relevant to energy forecasting for mechanized spaghetti production systems.

In relation to the time durations of the process operations that were applied to estimate the process energy consumptions (Section 2.6), with the exception of the manually operated units (i.e., flour sifting and spaghetti extrusion) (Figures 2–4), there were no statistically significant differences amongst the alternate spaghetti schemes (Table 1). The WFS and CDWFS schemes presented significantly lower flour sifting times vs. the CWFS ($p = .00$), while there was no significant difference between the WFS and CDWFS ($p = .312$). Indeed, only WF was sifted in the CDWFS scheme (Figure 4), thus justifying the comparable operation time for the CDWFS vs. WFS (Table 1). Conversely, regarding the manual spaghetti extrusion time, there was no significant difference between the CWFS vs. WFS ($p = .366$) or CDWFS ($p = .073$) (Table 1), while significant difference could be noted for WFS vs. CDWFS ($p = .013$). These findings could be attributed to influences from the different physicochemical properties of the feedstock applied and have been extensively discussed for spaghetti dough processing [1, 4, 39] and bread dough mixing operations [43, 57].

4. Study Limitations and Future Research

Although the present study provides some useful findings on the energy and product quality potentials for the investigated spaghetti schemes, some associated limitations must be recognized. The spaghetti processes were not optimized regarding product quality and energy consumptions. Dough processing time and speed of the applied electric mixer have been found to impact the quality of baked products [43, 57]. Although the dough-feel and visual inspection by experienced bakers are accepted conventional tests for satisfactory dough mixing and kneading [43], the reliability of such methods is dependent on the assessor. In the present study, this limitation was minimized through the use of one trained personnel for all the dough assessments. A future advanced study may consider a fully mechanized pilot spaghetti processing system where the electrical energy is measured directly and the flour and dough mixer energy are evaluated following the protocols of Wilson et al. [57] which incorporate the dough temperature rise to predict motor power losses. Similarly, the Farinograph method may be applied to study the rheological properties of the dough for the WFS, CWFS, and CDWFS to establish the appropriate dough development times and consistencies [1, 57]. Process and energy optimization opportunities (e.g., optimum CDWFS drying time) and sensory analysis of the spaghetti products could be explored towards sustainable industrial applications and consumer acceptance.

5. Conclusions

The blending of cassava flour or dewatered cassava pulp and wheat flour as feedstock for spaghetti production resulted in similar product yields as the conventional wheat flour spaghetti. Egg incorporation in the blended feedstock to augment the low protein content and binding properties of the cassava feedstock aided in the attainment of spaghetti products with similar moisture, crude fiber, carbohydrate, and energy contents as the commercial wheat spaghetti products. The cassava-wheat-based spaghetti processes resulted in products with cyanide concentrations within the acceptable safe limits for cassava food products. Process energy assessments indicate the cassava flour-wheat flour and cassava dough-wheat flour spaghetti schemes could potentially mitigate the process energy consumptions by 5.64% and 14.25%, respectively, as compared to the conventional wheat flour spaghetti scheme. Hence, the cassava-wheat spaghetti schemes are feasible alternatives to the conventional wheat flour scheme which when applied could contribute to reductions in the process energy cost and sustainable developments of spaghetti industries in resource-limited cassava growing regions. The cassava-wheat spaghetti production could therefore be explored as a socioeconomic development intervention in cassava-growing regions faced with challenges of high underutilized cassava resources and postharvest loss.

Abbreviations

CDWFS: Cassava dough-wheat flour-based spaghetti
CSP: Commercial spaghetti product
CWFS: Cassava-wheat flour-based spaghetti
DCP: Dewatered cassava pulp
HQCF: High-quality cassava flour
MC: Moisture content
RTPDU: Root and Tuber Products Development Unit
TDF: Total dietary fiber
TPA: Texture profile analysis
WAI: Water absorption index
WF: Wheat flour
WFS: Wheat flour-based spaghetti.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no competing financial interests or personal relationships that could be perceived as prejudicing the impartiality of the research reported.

Authors' Contributions

Richard Kingsley Padi did the conceptualization, methodology, investigation, validation, formal analysis, writing the original draft, and writing, which includes review and editing. Gregory Afra Komlaga worked on the supervision and writing, which includes review and editing. Firibu Kwasi Saalia did the supervision and writing, which includes review and editing.

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Supplementary Materials

Graphical abstract: the graphical abstract of the study. *(Supplementary Materials)*

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