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Valorization of cassava peel starch into functional liquid glucose via acid-catalyzed hydrolysis using sulfonated carbon catalyst and red ginger (*Zingiber officinale* var. *rubrum*) extract

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ABSTRACT

The growing gap between sugar consumption and domestic product in Indonesia Highlights the need for alternative sweeteners derived from renewable resources. This study investigates the synthesis of functional liquid glucose from cassava peel starch through hydrolysis catalyzed by sulfonated carbon derived from palm empty fruit bunches (TKS-SO_3H) and the enhancement of its antioxidant properties by red ginger extract. The TKS-SO_3H catalyst was prepared via carbonization at 350 °C followed by sulfonation at 180 °C, yielding an H+ ion concentration of 1.745 mmol/g. Hydrolysis was conducted at 100 °C for 60 minutes with a catalyst loading of 5% (b/v) and starch concentration ranging from 2.5 to 7.5%. The optimum glucose concentration of 4.14 mg/mL was achieved at 5% starch concentration, demonstrating the effective catalytic performance of TKS-SO_3H. subsequently, liquid glucose was combined with red ginger extract in various volume ratios (1:1-1:4 v/v) to assess antioxidant capacity using the DPPH radical scavenging assay. The formulation with a 1:4 glucose-to-ginger ratio exhibited the highest scavenging activity of 48.63% after 10 minutes, indicating a significant enhancement of functional properties. The findings suggest that cassava peel, an agricultural by-product, can be utilized as a sustainable feedstock to produce bifunctional liquid glucose using an environmentally benign heterogeneous catalyst, contributing to the development of value-added and health-oriented sweeteners.

1. Introduction

The valorization of agricultural residues into value-added bioproducts represents a key component of sustainable bioeconomy development, addressing both waste management and resource optimization challenges [1,2]. Cassava (Manihot esculenta) is among the most important starch-producing crops in tropical regions, generating substantial by-products such as peels, which account for nearly 10–15 % of the total tuber mass [3]. These cassava peels are often discarded as waste, contributing to environmental pollution due to their high organic content and slow biodegradability [4,5]. However, cassava peel is rich in carbohydrates (approximately 80 % starch and polysaccharides), small amounts of lignin and cellulose, and therefore represents an abundant, low-cost substrate for bioconversion into fermentable sugars and bio-based chemicals [4, 9].

The hydrolysis of cassava peel starch into glucose provides a strategic pathway to produce liquid sugars that can serve as feedstock for bioethanol, organic acids, and food-grade sweeteners [5,12]. Traditionally, enzymatic hydrolysis using α-amylase and glucoamylase has been widely applied due to its selectivity and mild operational conditions. Nevertheless, enzyme-based methods often suffer from high cost, long reaction times, and limited thermal stability, which restrict industrial scalability [6,12]. In contrast, chemical hydrolysis using acid catalysts offers a simpler and faster conversion process, yet conventional homogeneous acids such as H_2SO_4 and HCl pose drawbacks including corrosion, secondary pollution, and complex neutralization steps [7,13].

Recent developments have focused on heterogeneous solid acid catalysts, particularly sulfonated carbon-based materials, which combine the catalytic efficiency of strong acids with the reusability and stability of solid supports [2,8,10]. These catalysts are typically synthesized from lignocellulosic residues such as palm empty fruit bunches, lignin, or sucrose-derived carbon frameworks [10,11,14]. The sulfonation process introduces –SO_3H functional groups, providing Brønsted acidity that facilitates hydrolysis reactions through protonation of glycosidic oxygen and cleavage of C–O–C bonds in polysaccharides [1,13]. Structural characterization using FT-IR typically reveals absorption bands corresponding to O–H, C–O, and S–O groups, confirming the incorporation of acidic moieties [14–16]. Moreover, morphological analysis via SEM demonstrates that sulfonation enhances porosity and surface area, promoting substrate–catalyst interaction [3,11].

In addition to optimizing catalytic conversion, integrating functional enhancement into glucose products has gained

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increasing interest. Functional liquid sugars enriched with bioactive compounds can provide not only energy value but also health-promoting properties [6,17]. In this regard, red ginger (Zingiber officinale var. rubrum) extract has attracted attention due to its rich content of phenolics, flavonoids, and gingerols, which exhibit potent antioxidant, anti-inflammatory, and antimicrobial activities [7,8,18]. Several studies have reported that ginger extracts can scavenge free radicals effectively, mainly through hydrogen atom transfer and electron donation mechanisms, which stabilize reactive oxygen species and prevent oxidative stress [18–20].

Thus, combining cassava peel starch hydrolysis with the incorporation of red ginger extract offers a dual advantage: (i) the valorization of agro-waste into a renewable sugar source, and (ii) the development of a functional liquid glucose product with antioxidant capacity. The novelty of this study lies in the integrated utilization of two underexplored agricultural by products, cassava peel starch and oil palm empty fruit bunches, to produce a dual functional bio sweetener using a heterogeneous green catalyst. Unlike previous works that typically employ enzymatic hydrolysis of pure cassava starch or mineral acid catalysis, this research introduces a biocarbon based sulfonated catalyst (EFB-SO_3H) synthesized via an eco-friendly sulfonation route using hydroxyethylsulfonic and citric acids, ensuring high acidity and recyclability without toxic residues. Furthermore, the enhancement of the resulting liquid glucose with red ginger (*Zingiber officinale* var. *rubrum*) extract represents a novel functionalization strategy, yielding a natural sweetener with intrinsic antioxidant activity. Accordingly, this study aims to synthesize and characterize the EFB-SO_3H catalyst, apply it to cassava peel starch hydrolysis, and evaluate the antioxidant enriched liquid glucose as a sustainable product with added value for food and nutraceutical applications.Materials and Methods

1.1. Materials

The materials used in this study included oil palm empty fruit bunches (EFB) of the *Tenera* variety obtained from PT Perkebunan Nusantara XIII in Pelaihari, South Kalimantan; cassava peels sourced from local cassava-based food vendors in Banjarbaru City; red ginger; sodium hydroxide (NaOH); sodium chloride (NaCl); phenolphthalein; hydroxyethylsulfonic acid ($C_2H_6O_4S$); citric acid ($C_6H_8O_7$); dinitrosalicylic acid (DNS) reagent ($C_7H_4N_2O_7$); 2,2-diphenyl-1-picrylhydrazyl (DPPH); potassium tartrate ($K_2C_4H_4O_6$); oxalic acid ($H_2C_2O_4$); methanol (CH_3OH); and distilled water.

1.2. Method

Oil palm empty fruit bunches (EFB) were cleaned, cut into 2 cm pieces, and dried before being calcined at 350 °C for 60 minutes to produce carbon (EFB-C), which was then sulfonated by adding 3 mL hydroxyethylsulfonic acid and 1.5 g citric acid in 30 mL distilled water. The mixture was placed in a Teflon-lined stainless-steel autoclave and heated at 180 °C for 4 hours to obtain the sulfonated carbon catalyst (EFB-SO_3H), which was subsequently washed with 50% methanol and distilled water, and dried at 80 °C for 6 hours. Similarly, cassava peels were cleaned, cut into 1 × 1 cm pieces, blended with water, and filtered; the filtrate was allowed to settle, and the precipitate obtained was dried at 80 °C for 8 hours and sieved using a 40-mesh sieve to obtain cassava peel starch. The starch was then hydrolyzed by dissolving it in distilled water at various concentrations (0%, 2.5%, 5%, and 7.5% w/v) with the addition of 5% w/v sulfonated carbon catalyst in a three-neck flask connected to a reflux condenser, and the mixture was heated at 100 °C for 60 minutes. The resulting hydrolysate was filtered to obtain liquid glucose, whose glucose content was determined using the DNS method. Red ginger was peeled, washed, and blended with water at a 1:1 ratio (100 mL water: 100 g ginger), then filtered to separate the juice, which was left to stand for 24 hours to obtain pure ginger extract. Finally, the extract was mixed with liquid glucose in varying volume ratios (1:1, 1:2, 1:3, and 1:4 v/v) to produce antioxidant-enriched functional liquid glucose.

2. Results and Discussion

2.1. Characterization of sulfonated carbon catalyst

The sulfonated carbon catalyst synthesized from oil palm empty fruit bunches (EFB) underwent two main processes: carbonization at 350 °C and sulfonation using hydroxyethylsulfonic acid and citric acid. The carbonization step decomposed volatile compounds and lignocellulosic structures, forming amorphous carbon with initial microporosity [2,11]. This process facilitates the creation of polyaromatic domains that serve as anchoring sites for sulfonic groups in the subsequent functionalization step [14]. After sulfonation, the catalyst exhibited a deep black color, indicating successful incorporation of sulfur-containing groups., as shown in Figure 1. To observe the morphological structure of the EFB before and after calcination, a Scanning Electron Microscopy (SEM) analysis was performed, as presented in Figure 2.

Fig. 1. Preparation process of sulfonated biocarbon catalyst from oil palm empty fruit bunches (EFB)

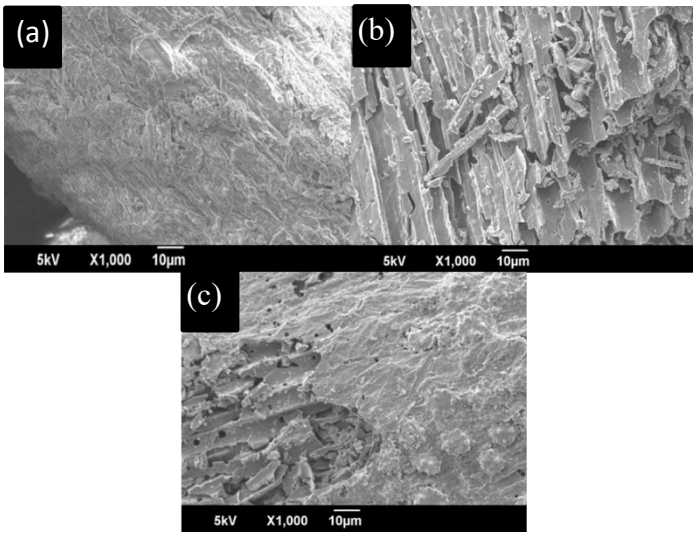


Fig. 2. SEM images of (a) EFB before calcination, (b) EFB after calcination at 350 °C (EFB-C), and (c) EFB after sulfonation (EFB-SO_3H)

Based on Figure 2, the morphological structure of the EFB

surface can be observed before calcination, after calcination, and after sulfonation. The morphology of the raw EFB (Figure 2a) appears fibrous, with no visible pores on the surface. This is because the pore structure of the oil palm empty fruit bunches has not yet opened and remains covered by lignin and other organic components. After calcination (Figure 2b), the EFB surface appears smoother, which is attributed to the effect of heat during the calcination process that leads to the formation of pores. These pores are created as the heat causes the decomposition of structural compounds. At a calcination temperature of 350 °C, the pores have transformed into carbon structures, as cellulose decomposition occurs in the temperature range of 300–350 °C (Browne, 2009). Figure 2c shows that the surface morphology of the sulfonated EFB becomes more open, with larger pores compared to the pre-sulfonated sample. During the sulfonation process, sulfonic acid groups (-SO_3H) were introduced and attached to the edges of polycyclic aromatic carbon structures. The sulfonating agent used was hydroxyethylsulfonic acid. Carbon activation during sulfonation enhances the structural stability of the carbon material, resulting in larger pores and an increased surface area, which can accelerate the hydrolysis process in liquid glucose production. Sulfonation is a chemical reaction that involves the incorporation of sulfonic acid groups (-SO_3H) into a molecule or ion, such as the introduction of –SO_3H groups into organic compounds (Rachim et al., 2012). SEM micrographs revealed a progressive transformation from fibrous EFB morphology to a porous carbon matrix after calcination, and further to an irregular, roughened structure post-sulfonation. The expansion of pores and formation of micro-cracks indicate partial oxidation and gas evolution during acid treatment, which increase the surface area available for catalysis [11,14]. Kirdant (2022) reported that such morphological alterations are essential for improving mass transfer and reactant adsorption in biomass-derived solid acids [3]. Collectively, the physicochemical analyses confirm that the EFB-SO_3H catalyst possesses sufficient acidity, porosity, and stability to facilitate starch hydrolysis under aqueous conditions.

The H^+ ion content increased significantly from 0.21 mmol H^+/g (calcined carbon) to 1.75 mmol H^+/g (sulfonated carbon), consistent with observations by Fitria et al. (2023) and Xu et al. (2025), who reported that dense –SO_3H grafting enhances acidity and catalytic activity toward polysaccharide hydrolysis [1,2]. Similarly, Al-Hamamre et al. (2024) found that lignin-derived sulfonated carbons maintain strong Brønsted acidity and thermal stability during repeated cycles [11]. This significant 735% increase in H^+ ion concentration indicates the successful attachment of –SO_3H groups to the EFB surface. The H^+ ions are bound to the sulfonate groups, which are expected to act as active catalytic sites during the hydrolysis process, facilitating the breakdown of cellulose into glucose. The addition of citric acid during the sulfonation process also contributed to the higher H^+ ion content in the sulfonated carbon compared to the non-sulfonated sample. The H^+ ion content of each sample is presented in Table 1.

Table 1. H^+ ion content

Sample	Concentration (mmol/g)
EFB-C	0.209
EFB-SO_3H	1.745

FT-IR analysis was conducted to identify the functional groups present in the samples, namely EFB, EFB-C, and EFB-SO_3H. As shown in Figure 3, The FT-IR spectra confirmed the introduction of key functional groups: a broad O–H stretching band at ~3470 cm^{-1}, C=O/C=C stretching near 1640 cm^{-1}, and a distinct S–O stretching band between 1180–1200 cm^{-1}, typical of sulfonated carbons [1,13,14], confirming the successful attachment of sulfonate groups to the biocarbon surface. The C–H (alkane) functional group was detected at 3000–2840 cm^{-1}, indicating the presence of carbon chains that can easily interact or bond with other groups or compounds.

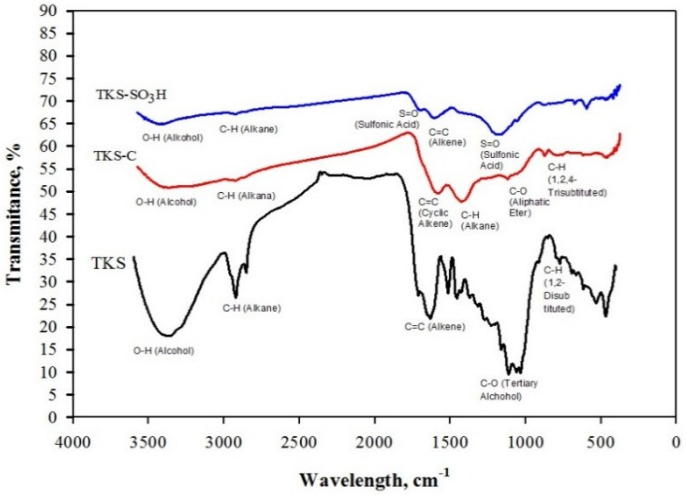


Fig. 3. FT-IR analysis results for EFB, EFB-C, and EFB-SO_3H

Similar S–O vibrational bands have been reported by Otieno et al. (2024) and Wongphan et al. (2024) as indicators of successful sulfonation in cassava starch derived and biomas carbon catalysts, respectively [15,16]. The presence of O–H and C–O groups suggest residual hydroxyl and carboxyl functionalities that enhance hydrophilicity and active site accessibility [3,14]. These features are essential for improving catalyst subtrate interactions during hydrolysis.

The structural and functional stability of the EFB–SO_3H catalyst also indicates its potential for reuse. The preserved surface morphology and consistent sulfonic functional groups observed after reaction suggest that the catalyst remains stable under hydrolysis conditions. Previous studies have reported that sulfonated carbon catalysts maintain more than 85–90 % of their activity after several cycles due to strong covalent bonding of –SO_3H groups to the carbon matrix [9,13]. Although catalyst reusability was not quantitatively evaluated in this study, the robust acidity and thermal stability of EFB–SO_3H imply promising potential for repeated use in subsequent hydrolysis cycles with minimal deactivation.

Overall, the spectral and morphological evidence (Figures 1–3) clearly demonstrate how structural modification and acid functionalization are directly linked to catalytic performance. The increased porosity and the formation of –SO_3H groups enhance proton availability, which in turn enhances the interaction between the starch molecules and the catalyst during hydrolysis.

2.2. Preparation process of cassava peel starch

In the preparation of cassava peel starch, the cassava peels were blended into a fine slurry (Figure 4a). The resulting filtrate was allowed to settle, and the precipitate was then dried to obtain cassava peel starch, as shown in Figure 4b. The final product was

a light brown starch powder with a yield of 40% and a particle size of 60 mesh.

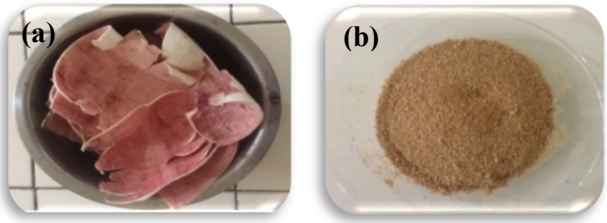


Fig. 4. (a) Cassava peel and (b) Cassava peel starch

The components contained in cassava peel are presented in Table 4.2. The results indicate that cassava peel starch has strong potential as a substrate for hydrolysis. A substrate acts as a reactant in a catalytic reaction to produce a product, which in this case is liquid glucose. The cassava peel contains 80.2% carbohydrates, serving as the main source for glucose production.

Table 2. Physical properties of edible film with the addition of kelakai extract

Component	Content (%)
Moisture	8.73
Ash	1.86
Protein	2.92
Fat	0.59
Carbohydrate	80.20

The SEM observation of cassava peel starch powder is shown in Figure 5. At a magnification of 1,500×, the cassava peel starch granules exhibited a generally spherical shape with non-uniform sizes ranging from approximately 4–10 µm. In comparison, other types of starch granules, such as those from *ubi alabio*, have larger particle sizes ranging from 10–40 µm. The smaller granule size and smooth morphology shown in Figure 5 support higher reactivity during hysrolysis because smaller particles enhance mass transfer and proton diffusion to glycosidic bonds.

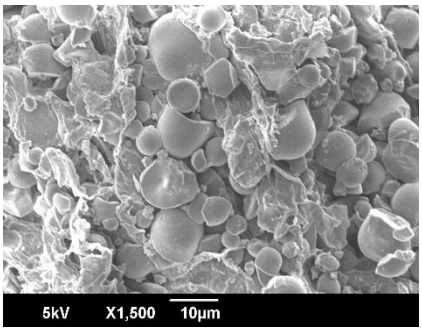


Fig. 5. SEM images of cassava peel starch

2.3. Hydrolysis of cassava peel starch using sulfonated carbon catalyst (EFB-SO₃H)

Starch hydrolysis is the process of breaking down amylose molecules into simpler components such as dextrin, isomaltose, maltose, and glucose. The hydrolysis process was carried out using a sulfonated carbon catalyst (EFB-SO_3H), which serves to break down cellulose into glucose. The –SO_3H groups on the surface of the EFB-SO_3H catalyst act as Brønsted acid sites that donate protons (H^+) to the glycosidic oxygen atoms in starch chains. This protonation weakens the C–O–C bonds, facilitating their cleavage and promoting the formation of glucose monomers. The high density of –SO_3H groups enhances proton transfer and accelerates reaction kinetics, resulting in higher hydrolysis efficiency under moderate temperature conditions (100 °C). Thus, the localized acidity of these functional groups directly influences the catalytic rate and overall glucose yield. Based on the experimental results, the highest glucose yield was obtained at a starch concentration of 5%. This finding was supported by visual observation of the resulting product, where a starch-to-catalyst ratio of 5% (w/v) produced the largest volume of liquid glusicose with relatively low viscosity. The comparison of product yield and volume obtained from the hydrolysis process using the catalyst is presented in Table 3 and Figure 6.

Table 3. Glucose product from cassava peel starch

Starch Concentration (w/v)	Product (mL)	Viscosity
0%	50	Low
2.5%	32	Low
5%	35	Low
7.5%	22	High

The glucose content obtained from the hydrolysis process using the catalyst was analyzed using the DNS method (Figure 6, inset). To determine the glucose concentration in the solution, a standard glucose solution was first prepared to create a calibration curve. The absorbance values obtained from the samples were then compared with this curve to calculate their glucose concentrations. The higher the glucose concentration in the solution, the greater the absorbance value, which was visually indicated by a more intense orange-brown color in the final DNS analysis. After calculations and measurements at different cassava peel starch concentrations, the resulting glucose content for each concentration is shown in Figure 6.

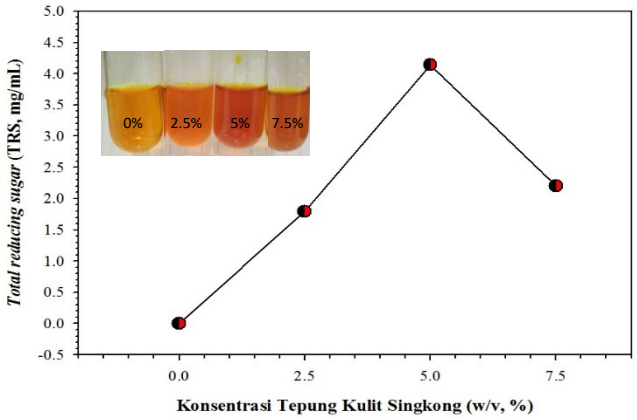


Fig. 6. Relationship between total reducing sugar (mg/mL) and starch concentration (%) at T = 100 °C, t = 1 hour

Based on Figure 6, it can be observed that at starch concentrations of 2.5% and 5%, the glucose concentration increased from 1.80 mg/mL to 4.14 mg/mL, and the volume of the resulting solution also increased from 32 mL to 35 mL. At a starch concentration of 7.5%, the glucose concentration

decreased to 2.20 mg/mL and the solution volume dropped to 22 mL. This decrease occurred because the high starch concentration hindered the catalyst's performance, leading to increased gelatinization. This behavior aligns with diffusion-controlled kinetics, where higher substrate density hinders catalyst–substrate interaction and limits proton accessibility [12, 17]. Similar results were reported by Fasheun et al. (2024), who observed a decline in hydrolysis rate at cassava-starch concentrations exceeding 5 % due to gel formation and reduced mass transfer [12]. The 5% starch concentration was observed as the optimum condition, yielding the highest glucose concentration with low viscosity. The use of TKS-SO_3H catalyst enhanced glucose production up to four times compared to hydrolysis without a catalyst.

Previous research by Fitria and Yulimasita (2016) produced liquid glucose from Nagara yam starch using amylase enzymes during liquefaction to form dextrin, followed by saccharification using glucosidase with varying incubation times. It was found that enzyme-based glucose production required more materials and longer processing time compared to using sulfonated carbon catalyst. The advantages of sulfonated activated carbon as a catalyst include resistance to acids and bases, stability under high temperature and pressure, inertness, and recyclability (recovery), making it an environmentally friendly catalyst that does not generate waste. FT-IR analysis of the native starch showed characteristic bands of O–H stretching at 3320–3400 cm^{-1}, C–H stretching at 2920 cm^{-1}, and C–O–C stretching of glycosidic linkages around 1020 cm^{-1} [15,16]. These spectral features align with the typical fingerprint region of amylose and amylopectin, confirming its suitability for hydrolysis. After reaction with the sulfonated carbon catalyst, new absorption bands appeared near 1720 cm^{-1} (C=O stretching), indicating cleavage of glycosidic bonds and formation of carbonyl groups from glucose and dextrin fragments [15,18].

In the present study, the use of EFB-SO_3H catalyst significantly enhanced hydrolysis performance compared with the control (no catalyst). The TRS yield increased more than fourfold relative to non-catalytic hydrolysis, demonstrating the catalytic role of –SO_3H groups in promoting proton-assisted cleavage of glycosidic bonds [1,13]. Halim et al. (2024) confirmed that acid hydrolysis preferentially attacks amorphous regions of starch granules, leading to partial depolymerization and formation of glucose monomers [18]. The reaction pathway involves protonation of the glycosidic oxygen followed by bond cleavage, forming carbocation intermediates that rapidly rearrange into glucose [13]. Microscopic analysis also supported these chemical findings: SEM images of cassava starch granules after hydrolysis showed surface erosion, fragmentation, and pore formation, consistent with observations by Cabeza et al. (2025) on starch hydrolysates after acid treatment [17]. Wongphan et al. (2024) further noted that thermal and mechanical processing enhance the accessibility of amorphous regions, which accelerate acid-catalyzed hydrolysis [16]. Therefore, the combination of moderate temperature (100 °C), sufficient catalyst acidity, and optimized starch concentration enabled efficient production of glucose-rich hydrolysates with minimal degradation. Table 3 and Figure 6 clearly show that the catalyst structure discussed earlier to its activity, as the enhanced surface acidity and porosity of EFB–SO_3H directly promote efficient starch hydrolysis under the optimized conditions. Compared with previous studies, this work is novel in using a sulfonated carbon catalyst derived from oil palm empty fruit bunches (EFB) for cassava peel starch hydrolysis under mild conditions. In addition, the process uniquely combines catalytic hydrolysis with antioxidant enrichment using red ginger extract, producing functional liquid glucose with added value.

2.4. Mixing of liquid glucose with ginger extract as and antioxidant source

Beyond its carbohydrate value, the hydrolyzed cassava-peel glucose was functionalized by incorporating red ginger (Zingiber officinale var. rubrum) extract as a natural antioxidant. The extract, rich in gingerols, shogaols, and flavonoids, exhibits high radical-scavenging activity through hydrogen atom donation and resonance stabilization of unpaired electrons [6–8,19].

The antioxidant capacity was quantitatively measured using the DPPH radical scavenging assay, which determines the free radical activity of the antioxidants present in the ginger extract. When the sample reacts with DPPH free radicals, a hydrogen atom transfer occurs from the antioxidant compounds in ginger, stabilizing the DPPH and forming reduced DPPH. This reaction is indicated by a color change from purple to yellow. The hydrogen or electron donated by the antioxidant prevents oxidation or neutralizes oxidized compounds by binding to reactive free radicals and molecules. The antioxidant activity of liquid glucose mixed with ginger extract for 1.5, 5, and 10 minutes of the glucose-ginger mixtures at ratios 1:1, 1:2, 1:3, and 1:4 (v/v) is shown in Figure 8. The process of hydrogen atom transfer from antioxidant compounds in ginger to DPPH molecules is illustrated in the following reaction (Fig 7).

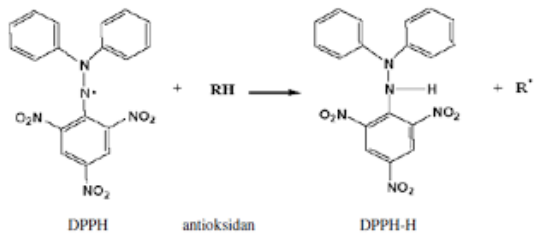
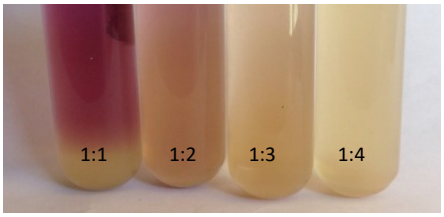


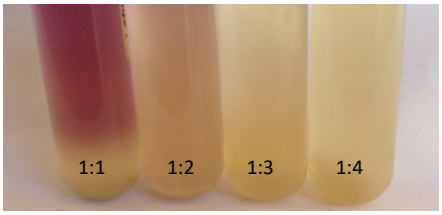
Fig. 7. Hydrogen atom transfer process from antioxidant compounds to DPPH molecules

Based on Figure 8, the highest scavenging activity of liquid glucose was observed in the fourth sample with a ratio of 1:4. Approximately 21.44% of DPPH free radicals were scavenged within 1.5 minutes, 39.34% within 5 minutes, and 48.63% within 10 minutes, demonstrating a time-dependent radical neutralization trend. Similar behavior was reported by Plana et al. (2025), who found that ginger extract capsules exhibited dose-dependent antioxidant activity linked to phenolic hydroxyl concentration [10]. Mustafa et al. (2023) and Ayustaningwarno et al. (2024) also confirmed that ginger extracts possess potent antioxidant capacities comparable to synthetic antioxidants such as BHT [6, 7]. The mechanism involves transfer of a hydrogen atom from the antioxidant (Ar–OH) to the DPPH radical, producing a stable, reduced DPPH–H species and a resonance-stabilized phenoxy radical [18–20]. The higher the concentration of ginger extract in the sample and the longer the reaction time

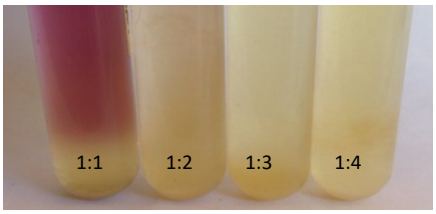
with the DPPH radical reagent, the greater the antioxidant activity in scavenging free radicals from DPPH. This occurs due to the transfer of electrons from antioxidant compounds to the unpaired electron on the nitrogen group within the DPPH molecular structure, indicated by a decrease in the intensity of the purple color and a reduction in absorbance percentage. The visible color shift from purple to yellow as DPPH radicals react with hydrogen atoms corresponds to a decrease in absorbance at 517 nm, indicating radical scavenging [20].



DPPH Test at t = 1.5 Minutes



DPPH Test at t = 5 Minutes



DPPH Test at t = 10 Minutes

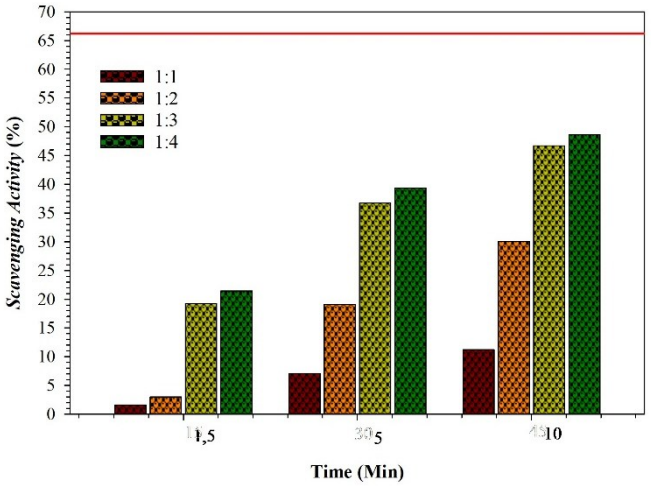


Fig. 8. Relationship between Scavenging Activity (%) and the Ratio of Liquid Glucose to Ginger Extract

Chemically, the phenolic hydroxyl groups in 6-gingerol and shogaol act as hydrogen and electron donors that react with DPPH radicals to form stable DPPH H products, thereby terminating the radical chain reaction [6,10]. In addition, these phenolic compounds can establish hydrogen bonds with the hydroxyl (OH) groups of glucose molecules, increasing solubility and stabilizing the antioxidant complex [7,20]. This dual interaction, involving radical quenching through hydrogen or electron transfer and hydrogen bond formation with glucose, explains the enhanced antioxidant activity observed in the glucose and ginger systems.

The red line in the figure represents the scavenging activity without the addition of liquid glucose, which was 43% at 1.5 minutes, 62% at 5 minutes, and 66% at 10 minutes. The decrease in absorbance indicates the scavenging (antioxidant) activity of the tested sample, namely liquid glucose. Christy et al. (2025) reported similar kinetics for red-ginger extract combinations, showing 50–60 % scavenging efficiency within 10 minutes [20]. In the present study, this strong correlation suggests that integrating ginger extract into hydrolyzed glucose not only imparts antioxidant activity but also enhances product aroma and sensory properties, as noted in other functional food formulations [17,19].

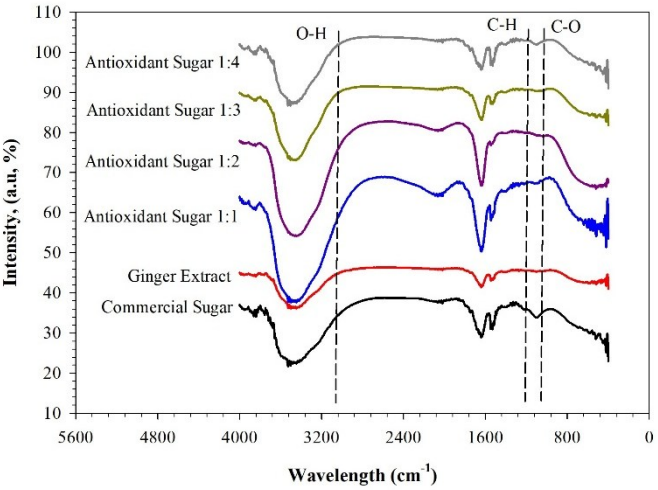


Fig. 9. FT-IR spectra of antioxidant glucose at various ratios, ginger extract, and commercial glucose

The crucial role of red ginger extract in enhancing antioxidant activity is clearly supported by the quantitative data in Figure 8. The stepwise increase in DPPH scavenging, from 21.44% to 48.63% as the ginger fraction increased, confirms that the extract provides the main source of active hydrogen and electron donors. The phenolic compounds, notably 6-gingerol and shogaol, effectively stabilize free radicals through resonance, thereby amplifying the overall antioxidant response of the glucose and ginger system. This correlation between extract ratio and scavenging efficiency demonstrates that the functional improvement of liquid glucose originates directly from the concentration-dependent activity of the bioactive molecules in red ginger, consistent with the findings of Mustafa et al. (2023) and Plana et al. (2025). Hence, the data validate the synergistic enhancement of antioxidant capacity achieved through the incorporation of red ginger extract.

The FT-IR analysis of liquid glucose with the addition of red ginger extract, as shown in Figure 9, indicates the presence of hydroxyl (-CHO) groups characteristic of the aldose class (Anggraeni et al., 2013). The functional groups identified in glucose are consistent with its molecular formula, $C_6H_{12}O_6$. The FT-IR spectra of antioxidant glucose at various mixing ratios exhibited no significant differences, as all samples displayed identical functional groups at similar absorption peaks. The C–O, C–H, and O–H stretching vibrations were detected at wavelengths of 1540 cm^{-1}, 1645.28 cm^{-1}, and 3476.48 cm^{-1}, respectively. The O–H functional group is associated with flavonoid compounds, which serve as the primary source of

antioxidant activity in the ginger extract. The presence of identical absorption peaks across ratios in Figure 9 confirms that mixing glucose with ginger extract did not alter molecular structure but rather produced stable hydrogen bonding between phenolic and hydroxyl groups.

Overall, the results clearly demonstrate that the sulfonated carbon catalyst derived from oil palm empty fruit bunches (EFB SO_3H) effectively facilitates starch hydrolysis due to its high acidity (1.745 mmol H^+/g) and porous structure, enabling optimal glucose production of 4.14 mg/mL at a 5% starch concentration. The subsequent enrichment with red ginger extract markedly enhanced antioxidant performance, achieving a 48.63% scavenging activity within 10 minutes. In addition to antioxidant performance, the introduction of phenolic compounds may also influence the stability of glucose solutions by retarding oxidative browning and microbial growth [8, 19]. The observed synergy between sulfonated carbon catalyzed hydrolysis and ginger derived antioxidants underscores the potential for developing functional liquid sugars derived entirely from renewable biomass. These findings confirm the synergistic relationship between catalyst properties and bioactive functionalization, where the physicochemical characteristics of EFB SO_3H ensure efficient hydrolysis kinetics, and the phenolic constituents of ginger provide strong hydrogen and electron donating capacities. This dual valorization, involving chemical conversion of cassava peel and bioactive enrichment with ginger, represents a circular approach that aligns with green chemistry principles and sustainable food innovation [1,4,5,14]. Collectively, these results justify the main conclusion that cassava peel, a low-cost agricultural residue, can be transformed into a high-value functional liquid glucose through a green dual-purpose process that combines catalytic conversion with antioxidant enhancement. This dual function approach represents an innovative pathway in sustainable bioproduct development and directly supports the study's core objective.

3. Conclusion

The overall process integrates three sustainable dimensions: (i) waste valorization, by utilizing cassava peel and oil-palm residues as feedstocks; (ii) green catalysis, through the use of recyclable sulfonated carbon catalysts rather than mineral acids; and (iii) functionalization, by enhancing product value with natural antioxidants. The optimal production of liquid glucose through the hydrolysis process was achieved at a starch concentration of 5% (b/v), resulting in a Total Reducing Sugar (TRS) content of 4.14 mg/mL. The best antioxidant glucose was obtained at a glucose-to-ginger extract ratio of 1:4, with a free radical scavenging activity of 48.63% after 10 minutes of reaction time. Covinich et al. (2025) emphasized that carbon-based heterogeneous catalysts are pivotal to transitioning biomass processing from batch chemistry toward circular biorefineries [14]. Likewise, Ben (2024) and Hierro-Iglesias et al. (2024) highlighted cassava-peel valorization as a cost-effective route to sustainable bioproducts [4,5].

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