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ORIGINAL RESEARCH ARTICLE

Purification of biodiesel-derived crude glycerol and its application in plasticizing cassava starch bioplastics

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ABSTRACT

This study focused on purifying crude glycerol, a by-product of biodiesel production, using acid-precipitation, methanol extraction, and adsorption with acid-activated charcoal. Among the acids tested—sulfuric, phosphoric, and hydrochloric—phosphoric acid proved most effective, producing the clearest glycerol with minimal salt deposition. The purified glycerol was then used to produce bioplastics, which were tested for mechanical properties. The results indicated that Phosphoric acid yielded the clearest glycerol with minimal salt deposition. The resultant salt, potassium phosphate (K_2PO_4), has potential as a fertilizer. The purified glycerol showed increased density and viscosity, indicating higher purity compared to crude glycerol. The density of the purified glycerol was closer to that of analytical-grade glycerol. Bioplastic 1 (using analytical-grade glycerol) exhibited the highest tensile strength, withstanding up to 4.3N and extending about 104mm before breaking. Bioplastic 2 (using glycerol purified with hydrochloric acid) withstood up to 4.1N, while Bioplastic 3 (using glycerol purified with acetic acid) endured the least stress, withstanding up to 3.8N and extending up to 87mm before breaking. The study demonstrates that phosphoric acid is an effective agent for purifying crude glycerol, significantly enhancing its quality. The purified glycerol, in turn, improves the mechanical properties of bioplastics, making them more durable and suitable for a range of applications. This process not only adds value to the biodiesel production by-product but also contributes to the development of stronger, more versatile bioplastics.

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INTRODUCTION

The increasing production of biodiesel has led to a significant rise in crude glycerol as a major co-product, with approximately 0.1 kg of crude glycerol generated for every 1 kg of biodiesel produced (Liu *et al.*, 2022). Crude glycerol, however, contains various impurities such as free fatty acids, salts, and methanol, which make its direct disposal both costly and environmentally detrimental. This has created a pressing need for effective purification processes that can convert crude glycerol into a more refined form, thereby unlocking its potential for use in numerous industries (Wan Isahak *et al.*, 2015a). Refined glycerol can serve as a valuable raw material in cosmetics, paints, automotive products, food, pharmaceuticals, and the pulp industry (Kongjao *et al.*, 2010, 2011). Additionally, purified glycerol can be utilized as a lubricant and plasticizer, particularly in the formation of starch-based bioplastics, where it plays a crucial role at the molecular level. The research problem addressed in this study stems from the environmental and economic challenges posed by the disposal of crude glycerol.

With the growing emphasis on sustainability, finding a method to repurpose this biodiesel by-product into a useful and environmentally friendly material is of paramount importance. The existing literature has explored various purification methods for crude glycerol, including distillation, filtration, chemical treatment, adsorption using activated carbon, ion-exchange using resin, extraction, decantation, and crystallization (Tan *et al.*, 2019). However, the focus has primarily been on methods tailored to purify crude glycerol based on its different properties, with less emphasis on locally adaptable solutions that could be implemented in regions where biodiesel production is on the rise (Ooi *et al.*, 2012). This study aimed to fill this research gap by developing a locally tailored purification process for crude glycerol, specifically designed for use in the production of starch-based bioplastics. The process involved a combination of acid-precipitation, methanol extraction, and adsorption with acid-activated charcoal. Three acids—sulfuric, phosphoric, and hydrochloric—were tested for their effectiveness in precipitating impurities from crude glycerol. Phosphoric acid emerged as the most effective, yielding the clearest glycerol with minimal salt deposition. The resultant salt, potassium phosphate (K_2PO_4), which was a by-product of this process, also holds economic value as a potential fertilizer, offering an additional benefit of this purification method.

The significance of this work lies in its innovative approach to not only purify crude glycerol but also explore the potential of underutilized cassava starch, particularly from non-food parts, in bioplastic production. Cassava starch is abundant in regions like Uganda, where cassava ranks as the second staple food (FEWSNET, 2023). While corn and potato starches have been the more commonly used sources in bioplastic production, this study highlights the advantages of using cassava starch, particularly from waste products such as peelings, which contain sufficient starch content for fermentation and subsequent bioplastic production (Ephraim *et al.*, 2014; Nuwamanya *et al.*, 2010). This approach not only supports environmental sustainability by reducing food waste but also contributes to food security by utilizing non-food parts of staple crops. The purification process developed in this study was methodical and thorough. Initially, the free fatty acids in crude glycerol, which constitute a significant portion (17%, w/w) of impurities, were separated through acidification. This step was crucial as these fatty acids, along with other impurities, often arise from the presence of alkaline catalysts and the concurrent saponification of oils during biodiesel production. The acid-precipitation method, following (Nanda *et al.*, 2015), involved adding 17 ml of 31.45% acid to 200 ml of crude glycerol at room temperature, followed by vigorous shaking and a settling period of 3 hours in a separating column. The glycerol-rich layer was then vacuum filtered using activated charcoal prepared with 25% calcium chloride and heated at 125°C for 2 hours. To further enhance the purity of glycerol, the study employed adsorption using acidified activated charcoal, which was particularly effective in removing oil-colored impurities (Nanda *et al.*, 2014; Nanda *et al.*, 2016; Suriaini *et al.*, 2021). The resultant glycerol was then compared against analytical-grade glycerol, using key properties such as density, alkalinity, pH, viscosity, and ash content as benchmarks. The purified glycerol demonstrated increased density and viscosity, indicating a higher level of purity and confirming that the purification process effectively removed impurities that contribute more to volume than mass (Nanda *et al.*, 2015).

In the final phase of the study, the purified glycerol was used to produce starch-based bioplastics, with cassava starch serving as the polymer matrix. Bioplastics were produced using both acetic and hydrochloric acids as hydrolyzing agents (Ahimbisibwe *et al.*, 2019a). Mechanical properties of the resulting bioplastics were tested using a universal testing machine, which revealed that Bioplastic 1, made with analytical-grade glycerol, withstood up to 4.3N of stress and extended 104mm before breaking (Ahimbisibwe *et al.*, 2019a). This was the highest performance observed among the samples, outperforming Bioplastic 2 (4.1N) and Bioplastic 3 (3.8N), which were made with glycerol purified using hydrochloric and acetic acids, respectively. The results demonstrated that purified glycerol not only meets ASTM standards (Astm, 2012) but also significantly enhances the mechanical properties of bioplastics, making them more durable and suitable for a wide range of applications (Ahimbisibwe *et al.*, 2019a; Gabriel *et al.*, 2021; Siddiqui *et al.*, 2024). This study successfully developed a locally tailored method for purifying crude glycerol, which, when used as a plasticizer, significantly improves the flexibility and strength of cassava starch-based bioplastics. The use of phosphoric acid in the purification process proved particularly effective, yielding glycerol that enhances the performance of bioplastics. This novel approach not only adds value to biodiesel by-products but also offers a sustainable solution for bioplastic production, contributing to environmental sustainability, waste management, and the development of bio-based materials. The findings underscore the potential of cassava waste starch in bioplastic production, offering a promising alternative to more commonly used starch sources and aligning with global efforts to reduce reliance on petrochemical-derived plastics.

MATERIALS AND METHODS

Source and initial treatment of crude glycerol

Crude glycerol used in this study was sourced from an ongoing biodiesel project at the National Crops Resources Research Institute. Upon collection, the glycerol was initially heated and placed in a separating column to eliminate any remaining biodiesel residues (Mitrea *et al.*, 2022). This preliminary step ensured the removal of extraneous biodiesel, resulting in a dark, viscous liquid ready for further purification (Chen *et al.*, 2020; Kumar *et al.*, 2021; Mitrea *et al.*, 2022). The crude glycerol was subsequently subjected to acidification, separation, and vacuum distillation processes to purify it. The properties of the crude glycerol were tested before and after purification to determine the effectiveness of the process (Gama *et al.*, 2016). The properties assessed included density, alkalinity, pH, water content, ash content, viscosity, boiling point, and energy content (Gama *et al.*, 2016, 2018; Harabi *et al.*, 2019).

Table 1. Variation of glycerol quality at different stages of purification from crude, acidified to purified glycerol.

Property	Crude glycerol	Acidified glycerol	Purified glycerol	ISO standard	Method
Glycerol content (%)	77.4	89.4	99.78	99.8	Through *et al.* (2019)
Density (g/ml) at 27°C	1.23	1.25	1.26	1.259 g/ml	Nanda *et al.* (2014)
Alkalinity	155.47	443.89	88.26		Nanda *et al.* (2014)
pH	11.12	6.74	6.70	**7**	Nanda *et al.* (2014)
Moisture content (%)	2.5	0.25	0.15		Astm (2022)
Free fatty acids (%)	2.84	0.84	0.1	0.05	Abuhabaya *et al.* (2013)
Ash content (%)	2.4	0.007	0.002		Thompson & He (2006)
Viscosity Dynamic (Dp AT 40°C)	50.500	102.300	105.500	105.68	Kongjao *et al.* (2010, 2011)
Viscosity Kinematic(m^2/s)		123±1	142±2	142.5	
Boiling point			288°C	290 °C	
Melting point			15.3°C	17.8 °C	
Gross energy (cal/g)	3685	5810.3	5832.5		Wan *et al.* (2015)

Purification of crude glycerol

The purification of crude glycerol was achieved through a combination of acidification and distillation. Three different acids—hydrochloric, sulfuric, and phosphoric—were added to the crude glycerol to facilitate separation into three layers: free fatty acids at the top, a glycerol-rich middle layer, and salt residues that settled at the bottom (Nanda *et al.*, 2015). The glycerol -rich layer was further purified using the method described by (Nanda *et al.*, 2014). This approach effectively removed impurities, yielding a purified glycerol product suitable for further analysis (Cai *et al.*, 2013; Kongjao *et al.*, 2010; Nanda *et al.*, 2015; Wan Isahak *et al.*, 2015b).

Determination of density

The density of the crude and purified glycerol was determined following the ASTM D891-95 (2004) standard. First, the weight of a dried beaker was recorded. Water was then added to the beaker at room temperature (26 ± 1˚C), and its mass was measured to calculate the volume of the beaker (Armylisas *et al.*, 2023). The crude and purified glycerol samples were then filled into the dried beaker at the same temperature, and their masses were noted. The density was calculated by taking the ratio of the sample's mass to the beaker's volume (Luo *et al.*, 2018).

Determination of alkalinity

Alkalinity was measured using the IUPAC-ACD (1980, 6th edition) method as described by (Nanda *et al.*, 2014 and 2015). Hydrochloric acid (HCl) was added to the glycerol sample until the pH reached 4.2, at which point all alkaline compounds in the sample were neutralized (Pal & Chaurasia, 2016). The alkalinity was calculated using the following formula:

$$\text{Alkalinity} = \frac{100 \times V \times N}{W}$$

Where,

V is the volume (ml) of the HCl solution consumed during titration; N is the normality of the HCl solution, and W is the weight (g) of the crude glycerol used.

Determination of pH

The pH of the glycerol samples was determined using a Mettler-Toledo pH meter. A 200 ml sample of glycerol was placed in a beaker, and the pH meter probe was submerged until fully immersed in the glycerol. The pH reading was recorded, and the process was repeated three times to obtain average values (Nesrine *et al.*, 2020).

Determination of water content

Water content in both crude and purified glycerol samples was measured using a hydrometer. This method provided a straightforward and reliable assessment of the moisture content in the samples (Armylisas *et al.*, 2023; Pal & Chaurasia, 2016).

Determination of ash content

Ash content was determined according to ISO 2098-1972 (Sinaga *et al.*, 2019). A 1 g sample of glycerol was burned in a muffle furnace at 750°C for 3 hours. The remaining residue was weighed to calculate the ash content, providing an indication of the inorganic material present in the glycerol (Armylisas *et al.*, 2023; Pal & Chaurasia, 2016).

Viscosity measurement

Viscosity was measured using a FUNGILAB Alpha series viscometer (Serial Number: Aph 101043). This instrument provided precise readings of the glycerol's flow resistance, an important parameter in assessing the quality of the purified product (Armylisas *et al.*, 2023; Harabi *et al.*, 2019).

Boiling point determination

The boiling point of the glycerol samples was determined by placing 2-3 ml of the sample in a test tube along with a thermometer tied to an inverted capillary tube. The test tube was then immersed in a beaker containing paraffin oil, which was heated on a hot plate (Hambali *et al.*, 2022). The temperature at which rapid air bubbles emerged from the capillary tube was recorded as the initial boiling point. The heating was then ceased, and the temperature at which the last bubble appeared was noted as the boiling temperature (Rywińska *et al.*, 2013).

Energy content measurement

The energy content of the crude and purified glycerol was measured using a bomb calorimeter, model C2000. This method involved combusting the glycerol sample in a controlled environment to determine the heat energy released, providing an indication of the sample's calorific value (Chen *et al.*, 2018; Yung *et al.*, 2021).

Determination of bioplastic properties

The mechanical properties of the bioplastics produced from the purified glycerol were assessed, focusing on tensile strength, elongation before break, and Young's modulus. The bioplastics were cut into dog bone shapes, and their dimensions (length, width, and thickness) were measured before testing. The tensile properties were measured using a universal testing machine, following the procedure outlined by (Basiak *et al.*, 2018, 2022) The machine was set to a crosshead speed of 50 mm/min, with data collection at 20 points per second at room temperature. Tensile modulus, defined as the ratio of tensile stress to strain, was also determined, alongside tensile elongation, which measured the percentage increase in length before the material broke under tension (Buddhakala & Buddhakala, 2023; Censi *et al.*, 2022).

Melting point determination

The melting point of the bioplastics was determined by finely powdering the material and packing it into a capillary tube to a depth of 1-2 mm. The capillary tube, containing a thermometer, was inserted into a melting point apparatus, which was heated at a rate of 10-15°C per minute until approximately 15°C below the expected melting point. The heating rate was then reduced to 1-2°C per minute until the material melted. The temperature at which the bioplastic began to flow out of the capillary tube was recorded as the melting point (Amin *et al.*, 2019).

RESULTS AND DISCUSSION

Purification methods and challenges

Glycerol, a versatile and valuable resource, has applications that span a wide array of industries, from domestic uses to extensive industrial applications in cosmetics, beverages, and pharmaceuticals (Christy *et al.*, 2018; Fauziyah *et al.*, 2021; García *et al.*, 2014; Vassilev *et al.*, 2017). This unique by-product of biodiesel production can be utilized in both its pure and crude forms. In its crude state, glycerol can be incorporated into briquettes to enhance their energy content, while in its purified form, it has numerous industrial applications. Purification processes can refine glycerol to reach three primary grades: technical grade, pharmaceutical grade, and food-grade (Ardi *et al.*, 2015). In this study, technical-grade glycerol was produced, demonstrating the potential for its use in various industrial processes. The glycerol used in this study was sourced from the Research Institute and initially appeared very dark due to the presence of non-volatile decomposed compounds such as oxidized triacylglycerols and free fatty acids (FFA). The purification of crude glycerol, especially that generated from the transesterification of used oils for biodiesel production, requires rigorous steps including both physical and chemical treatments (Kongjao *et al.*, 2010, 2011). Separation challenges during the purification process can make the procedure costly; however, the value-added products derived from purified glycerol are often more rewarding.

To purify glycerol, a sequence of steps is typically followed, tailored to the specific method employed. In this study, the process began with neutralization, followed by methanol removal, adsorption by activated carbon, and finally, separation by vacuum distillation. This method is consistent with the approach used by (Pal *et al.*, 2018; Pal & Chaurasia, 2016). Hydrochloric, sulfuric, and phosphoric acids were utilized as acidifying agents, with phosphoric acid yielding the least amount of salts and producing the clearest solution. This outcome aligns with the findings of (Nanda *et al.*, 2015; Nanda *et al.*, 2014), who suggested that phosphoric acid is the most effective acidifying agent for glycerol due to its ability to produce commercially usable salts with minimal further cleansing. The process of neutralization, stripping, filtration or centrifugation, and vacuum distillation is a common purification pathway for glycerol (Ardi *et al.*, 2015). Among the available purification techniques, the combination of chemical treatment, conventional filtration, and vacuum distillation—similar to the method used by (Mcquade & Creighton, 1970)—proved effective in this study. While vacuum distillation is known for its high energy requirements and sensitivity to feed stream variations, it remains the most suitable method for achieving the highest purity level of glycerol (Pal *et al.*, 2018; Pal & Chaurasia, 2016). However, the economic feasibility of this method can be challenging for small and medium enterprises due to its exorbitant costs.

Table 2. Showing the initial and final dimensions of the bioplastics before and after tensile strength and moduli tests.

	Width (mmm)	Thickness (mm)	Original Length (mm)	Final Length (mm)	Extension (mm)	Percentage extension (%)
Sample 3	6.31	0.78	34.86	56.37	21.51	61.73
Sample 1	6.35	0.48	36.28	43.16	6.88	18.96
Sample 2	6.34	0.5	34.49	48.03	13.54	39.26

Table 3. Illustrating the variation in the extension, tensile strength and the ultimate young Modulus of the three bioplastics.

Sample	Young modulus (MPa)	Tensile strength (MPa)	Percentage extension (%)
Sample 3	157.3±2.66	42.3±0.63	119.0763±0.97
Sample 1	56.3±1.38	26.5±0.34	18.964±0.35
Sample 2	104.6±0.87	32.4±1.57	39.258±0.53

Impacts of purification on glycerol properties

The physical properties of glycerol, such as density, viscosity, and energy content, were significantly altered following purification. The increase in density after purification suggests that the impurities removed contributed more to the volume than to the mass of the crude glycerol. Both dynamic and kinematic viscosities increased, indicating that the removal of impurities enhances intermolecular and surface forces, such as cohesive forces between molecules, thereby increasing viscosity (ISBC 2012; Anđelović *et al.*, 2022). This increase in viscosity is crucial for applications in the food and pharmaceutical industries, where glycerol is used to adjust the flow properties of various products. Methanol, with its low evaporation temperature of 65°C, was easily removed during the purification process. Methanol is favored in glycerol purification for its cost-effectiveness, high reactivity, and lack of azeotrope formation, which simplifies methanol recovery (Ardi *et al.*, 2015). However, the acidification step introduced complexities, as an increase in pH during this step improved purity but reduced glycerol yield by increasing salt and FFA contamination levels, particularly when hydrochloric acid was used (Ben *et al.*, 2022; Epure *et al.*, 2011; Glycerol: Properties and Production, 2010).

Effect of purification on glycerol

The progressive transformation of glycerol from a crude, dark liquid to a yellowish glycerol-rich layer, and finally to a pure, colorless, and odorless valuable liquid, demonstrates the effectiveness of the purification process (Takamura *et al.*, 2012; Zhang & Wu, 2015). This transformation is significant not only in terms of aesthetic qualities but also in enhancing the functional properties of glycerol for industrial applications. Initially, filtration was employed to remove solid impurities, resulting in the first state of crude glycerol. Following this, acidification was conducted to produce the yellowish glycerol-rich layer, where free fatty acids (FFAs) and salts were separated (Basiak *et al.*, 2018; Ben *et al.*, 2022; "Glycerol: Properties and Production," 2010). The final step involved vacuum distillation and adsorption using activated charcoal, which effectively removed the remaining impurities, yielding clear, technical-grade glycerol. This purified glycerol is suitable for high-value applications such as in the production of bioplastics.

Effect of purifying acid on glycerol quality

Acidification emerged as the most critical step in the purification process, as it effectively separated glycerol from free fatty acids and salts. Among the acids tested, phosphoric acid demonstrated superior performance, producing the clearest glycerol-rich layer. This clarity indicates that most of the colored impurities were successfully suspended as FFAs, while solid impurities, including salts, settled at the bottom. The choice of acid is pivotal because the acid's ability to decolorize and yield a higher quantity of glycerol determines the overall efficiency of the purification process. Hydrochloric acid, while also effective, yielded less clear glycerol and produced a higher amount of salts compared to phosphoric acid. Sulfuric acid was less effective in decolorization and glycerol yield, making it a less favorable choice. The resultant glycerol, regardless of the acid used, was further purified using vacuum distillation and adsorption by activated charcoal, ensuring that the final product met the stringent requirements for use in bioplastic production. This purification process, particularly the acidification step, is supported by findings in similar studies (Nanda *et al.*, 2015; Nanda *et al.*, 2014) (Kongjao *et al.*, 2010, 2011).

Performance comparison of glycerol properties in reference to ASTM standards

To assess the effectiveness of the purification process, the properties of glycerol were analyzed before and after purification and compared against ISO and ASTM standards. As shown in Table 3, the purification process significantly improved the quality of glycerol. The increase in glycerol purity was directly correlated with an increase in density, which in turn enhanced the viscosity (Nanda *et al.*, 2015). Higher viscosity is desirable as it broadens the applicability of glycerol in various industries, including food, cosmetics, and pharmaceuticals, where glycerol is often used to adjust viscosity. The relationship between viscosity and temperature, particularly the reduction in drag force at higher temperatures, underscores the importance of regulating temperature during the plasticization of starch for bioplastic production (Hájek & Skopal, 2010; Nanda *et al.*, 2015; Yang *et al.*, 2008). The ash content of the glycerol sample, a measure that typically varies depending on the catalysts and chemicals used during purification, was reduced to 0.002% in the final product, aligning with ISO standards (Coffinet *et al.*, 2015). The choice of acid in the purification process, particularly phosphoric acid, was critical in achieving this low ash content. Phosphoric acid not only produced the least ash but also yielded salts with potential applications as fertilizers, adding an extra dimension of value to the purification process (Ardi *et al.*, 2015; Yuliana *et al.*, 2021). The melting point of the purified glycerol was slightly lower than the ISO standard, which, while indicating the presence of soluble impurities, proved advantageous in the context of bioplastic production. A lower melting point facilitated easier blending with starch, a crucial step in bioplastic synthesis (Kim & Boehman, 2021; Kumar *et al.*, 2019). The boiling point of the purified glycerol was recorded at 288°C, slightly below the standard by 2°C, implying a marginal reduction in the energy required for vaporization, which could translate to energy savings during industrial processing. The purified glycerol's free fatty acid content, although double that of the ISO standard, remained within acceptable limits for technical-grade glycerol. These remaining FFAs could potentially be further refined to produce additional glycerol, adding yet another layer of sustainability to the process (Tan *et al.*, 2013; Wan Isahak *et al.*, 2015b).

Economic and environmental implications of glycerol purification

The economics of glycerol purification are favorable, especially considering that materials such as activated charcoal and methanol can be reused, significantly reducing production costs.

Additionally, the salts generated during the purification process, such as K_2HPO_4 produced by phosphoric acid, have high market value as food additives, fertilizers, and for other domestic uses (Nanda *et al.*, 2014 and 2015). The use of glycerol in polymer production not only contributes to solving the global plastic waste problem but also opens new avenues for the development of sustainable materials.

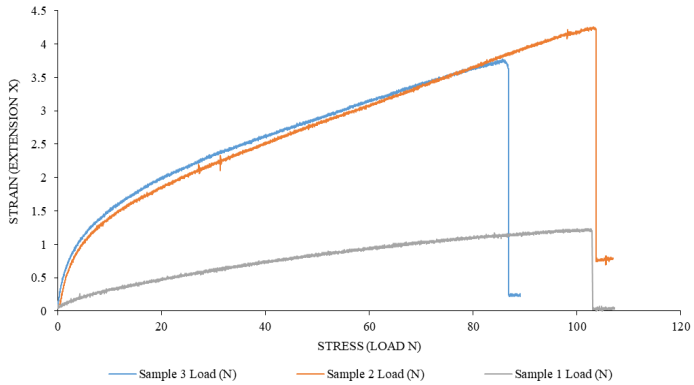

Figure 1. *Stress-Strain assortment of the three bioplastics under varying forces.*

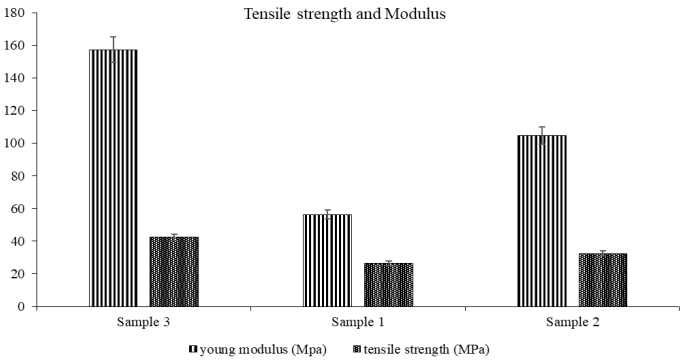

Figure 2. *Comparison of the tensile strength and modulus of the bioplastics.*

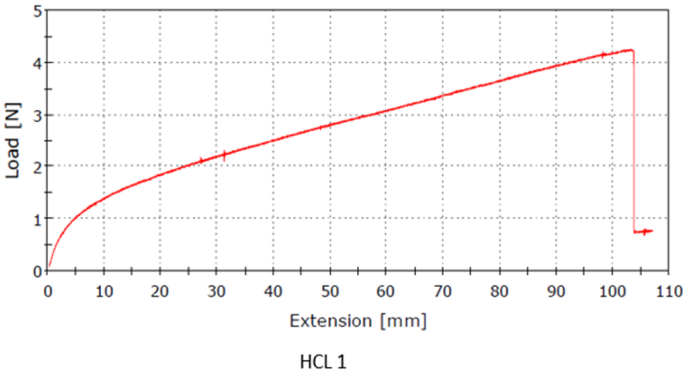

Figure 3. *Changes in original length by extension with varying loads for bioplastic one.*

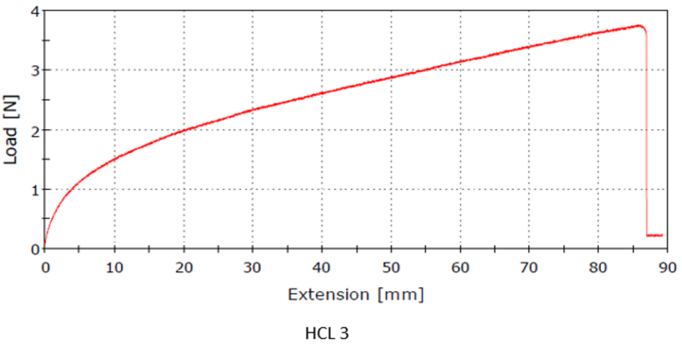

Figure 4. *Changes in original length by extension with varying loads for bioplastic three.*

Applications of purified glycerol in bioplastic production

After ensuring the quality of the glycerol through various tests, it was utilized as a plasticizer in the production of thermoplastic starch bioplastics. The purified glycerol enhanced the plasticity and flexibility of the bioplastics, which is crucial for their mechanical properties and degradability. The production process involved three major steps: thermosetting, drying, and molding. The glycerol's role as a plasticizer at high temperatures facilitated the conversion of starch granules into a strong thermoplastic starch, forming a durable polymer upon cooling (Abbott *et al.*, 2014, 2017).

Bioplastic quality assessment

The purified glycerol was utilized to produce three different bioplastics, labeled as bioplastic 1, bioplastic 2, and bioplastic 3. Bioplastic 1 was synthesized using commercially available analytical-grade glycerol, serving as a benchmark. Bioplastic 2 and bioplastic 3 were produced using glycerol purified through the process described in this study, with hydrochloric acid and acetic acid as the hydrolyzing agents, respectively. The mechanical properties of these bioplastics, including tensile strength, Young's modulus, and elongation before break, were evaluated to determine their suitability for industrial applications (Figure 2) (Rosenboom *et al.*, 2022). For the mechanical tests, the bioplastics were cut into dog bone shapes, and their initial dimensions were carefully measured as outlined in Table 4. The universal testing machine was employed to assess tensile strength, which measures the force required to break the bioplastic. Young's modulus, a ratio of tensile stress to strain, was also determined to evaluate the material's stiffness. The tensile elongation, which indicates the percentage increase in length before breaking under tension, was measured to assess the flexibility of the bioplastics (Gironi & Piemonte, 2011; Harnkarnsujarit *et al.*, 2021; Rosenboom *et al.*, 2022). The mechanical tests revealed that bioplastic 1, produced with commercial glycerol, exhibited the highest tensile strength and Young's modulus, indicating superior stiffness and resistance to deformation. Bioplastic 2, produced using glycerol purified with hydrochloric acid, showed slightly lower tensile strength but higher elongation before break, suggesting a more flexible material. Bioplastic 3, hydrolyzed with acetic acid, displayed the lowest tensile strength and Young's modulus, but the highest elongation, making it the most flexible of the three. These variations in mechanical properties highlight the impact of the purification process and the choice of acid on the final product, underscoring the importance of optimizing these parameters to produce bioplastics with desired characteristics (Coppola *et al.*, 2021; Harnkarnsujarit *et al.*, 2021; Razza *et al.*, 2015). The thermal properties of the bioplastics were also assessed, with a particular focus on melting point, as equipment for measuring fractional crystallinity and glass transition temperature was not available. The melting point tests, conducted using a capillary tube method, revealed that bioplastic 1 had the highest melting point, followed by bioplastics 2 and 3. This trend aligns with the mechanical properties, where bioplastic 1 demonstrated the

greatest resistance to thermal deformation, making it suitable for applications requiring higher thermal stability (Coppola *et al.*, 2021; Razza *et al.*, 2015).

This study successfully demonstrated the purification of crude glycerol to produce a high-quality, technical-grade product suitable for bioplastic production. The purification process, particularly the choice of acid during acidification, played a critical role in determining the quality of the final glycerol. The mechanical and thermal properties of the bioplastics produced from the purified glycerol indicate their potential for a range of applications, with the flexibility and thermal stability of the material being key factors in their suitability for specific uses. This research contributes to the growing body of literature on sustainable bioplastic production, offering a viable method for utilizing glycerol, a by-product of biodiesel production, in an environmentally friendly and economically viable manner. Future studies could explore further refinement of the purification process to enhance glycerol purity and expand the range of bioplastics that can be produced from this versatile material (Gironi & Piemonte, 2011; Harnkarnsujarit *et al.*, 2021; Kapanen, 2012; Razza *et al.*, 2015). The extension in length after break for the three bioplastics for the varying loads applying a given force on the plastic and the change in length revealed by the ruler laid at the bottom. Bioplastic 3 had the longest extension though it had a wider cross-sectional area as shown in the graphical abstract.

Tensile strength and modulus

Bioplastic 1 withstood the least stress and had the lowest modulus implying its use should be limited to simple applications like covering food. Bioplastic 2 withstood the highest stress, and its application can be for slightly harder activities like carrying staff since it registered the highest modulus (Figure 2). The comparison between the limit before which a material withstands the applied force before fracture and the ratio of the stress to strain of the bioplastics is shown to be highly correlated. Sample 2 is most suitable for stronger and more intense application because it can withstand a greater force with minimal extension. Increase in tensile strength is more expressed in a material than its modulus and bioplastic 3 could withstand the most average stress before fracture or crack. Decrease in the strength of a material reduces its applicability so there is limited use for bioplastic one (Figure 2).

Load and resultant extension

Sample 1 withstood up-to 4.3N as shown in Figure 3, Sample 3 endured the least stress of up-to 3.8N. This variation is as a result of the different strength exhibited by the two bioplastics in figure 1 . Bioplastic 1 had the widest area under the curve suggesting the highest elastic energy potential compared to bioplastic 3 whose area is smaller. The elastic energy potential reveals the potential energy of the bioplastics a result of deformation by the force applied (Figure 3). Table 3 shows the modulus of the three bioplastics increased from bioplastic 1 to 3 and this was the same trend as tensile strength where bioplastic 3 extended most under the highest stress before breaking. In all aspects, bioplastic 2 performed moderately with an average modulus and tensile strength and the least extension because it withstood the least stress before break point (Figure 4. The increase in tensile strength indicates an ability to be used for various applications. A high modulus for a polymer implies an increase in its strength but not necessarily its ductility. The ductility of the bioplastics was however not measured as earlier proposed because a ductilimeter was not accessed (Figures 3 and 4).

Mechanical properties and degradability of bioplastics

The study produced seven bioplastics, of which three were subjected to mechanical testing. The results indicated that bioplastic 3, made with locally purified glycerol and hydrolyzed by acetic acid, exhibited the highest strength, underscoring the superiority of acetic acid as a hydrolyzing agent (Abang *et al.*, 2023; Ayala *et al.*, 2023; Cinar *et al.*, 2020). The tensile strength and modulus of elasticity were key indicators of the bioplastics' suitability for various applications, with bioplastics 1 and 3 showing potential for more demanding uses due to their higher tensile strength and modulus (Figure 4). Degradation tests conducted in both open environments and laboratory settings revealed that the bioplastics were susceptible to degradation through a combination of natural processes, such as microbial activity, UV and heat radiation, and hydrolysis by water (Ahimbisibwe *et al.*, 2019b; Cucina *et al.*, 2022; Dibha *et al.*, 2023; Zhao *et al.*, 2023). The hydrophilic nature of starch, combined with the biodegradable properties of the bioplastics, makes them a promising alternative to conventional plastics, particularly in applications requiring controlled degradation (Ahimbisibwe *et al.*, 2019a).

Conclusion

The urgency of replacing non-degradable plastics with biodegradable alternatives has never been greater, driven by the escalating environmental impact of single-use disposables, particularly in packaging. Bioplastics derived from renewable sources offer a promising solution, yet challenges related to their quality and production costs remain formidable. However, ongoing research is beginning to unlock new possibilities, such as the use of glycerol as a plasticizer, which has shown considerable potential in enhancing the mechanical properties of bioplastics and broadening their applicability. The incorporation of nano-fillers, cellulose, and other reinforcing agents presents an opportunity to significantly improve the strength and versatility of these materials, positioning them as more competitive alternatives to conventional plastics. In particular, the challenge of purifying crude glycerol obtained from used oxidized oil—a critical step in making the biodiesel process economically viable. This purification process is notably non-energy intensive and adds value not only to the crude glycerol itself but also to the entire biodiesel production chain. The purified glycerol, which aligns well with ASTM standards despite some minor divergences, demonstrated advantageous properties such as a lower melting point. This

characteristic eased its dissolution in the production of bioplastics, underscoring its suitability as a high-value resource with significant application potential. This locally tailored purification method offers emerging biodiesel projects an effective means of utilizing glycerol, thereby enhancing the overall economic and environmental viability of these initiatives. The research underscores the critical role that glycerol, once purified, can play in the future of bioplastic production. As the drive to replace non-degradable plastics intensifies, these findings offer a path forward for the development of more sustainable, cost-effective, and high-performance bioplastic materials. By continuing to refine these processes and exploring new applications for purified glycerol, the potential for bioplastics to replace conventional plastics becomes increasingly tangible, paving the way for a more sustainable future.

DECLARATIONS

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