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CASSAVA-BASED BIOPLASTIC AS A CARRIER MEDIUM FOR SLOW-RELEASE FERTILIZER

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Abstract

The rapid nutrient release of conventional fertilizers often leads to resource inefficiency, environmental pollution, and a continuous increase in subsidized fertilizer demand in Indonesia. This study aimed to develop cassava starch (Manihot esculenta Crantz)-based bioplastic as a carrier medium for urea slow-release fertilizer (SRF). The bioplastic was further analyzed for its mechanical properties, biodegradability, and nutrient release efficiency. The research method involved cassava starch preparation, bioplastic fabrication using cassava starch, polyvinyl alcohol (PVA), and glycerol mixtures, followed by testing of water resistance, tensile strength, elongation, Fourier Transform Infrared (FTIR) analysis, and SRF release performance. The results showed that bioplastic containing fertilizer (BP) exhibited higher water absorption, with water resistance of 73.45%, compared to bioplastic without fertilizer (BP0), which showed 67.44% water resistance. Mechanical testing revealed that bioplastic without fertilizer had a higher tensile strength (0.99 MPa) than bioplastic containing fertilizer (0.50 MPa). Although the tensile strength did not meet the Indonesian National Standard (SNI ISO 527-1:2016), which requires values between 24.7–302 MPa, the elongation properties of both samples met the standard range of 21–220%. Functional group analysis using FTIR indicated changes in the chemical structure of the bioplastic due to fertilizer addition, evidenced by a shift in the FTIR absorption peak at 2164.13 cm^{-1}, corresponding to the isocyanate group. The urea slow-release test conducted over six days showed a nutrient release efficiency of 66% for the bioplastic-embedded urea fertilizer (BP) compared to the direct use of urea fertilizer. Overall, this study demonstrates that cassava starch-based bioplastic has strong potential as an efficient carrier material for SRF applications.

Keywords: *bioplastic, cassava starch, slow-release fertilizer, urea fertilizer, biodegradability*

Introduction

Urea fertilizer contains a high concentration of nitrogen, ranging from 45% to 56%, which is significantly higher than other fertilizers such as NPK (15%–20%) and ammonium sulfate (21%). As a dominant source of nitrogen, urea has physicochemical properties that enable rapid nutrient release after application to the soil. Under favorable environmental conditions, urea undergoes rapid hydrolysis into ammonia and carbon dioxide. Although this process efficiently supplies nitrogen to plants, it also poses several agronomic and environmental challenges. The released ammonia can volatilize into the atmosphere as ammonia gas (NH_3) or be oxidized into nitrate (NO_3^-) through nitrification, which is easily leached by water. Uncontrolled nitrate leaching into groundwater and surface water not only reduces fertilization efficiency but also leads to nutrient wastage and environmental degradation. Moreover, the rapid release of nutrients may disrupt soil structure and decrease soil quality in the long term (Jaya et al., 2024).

This problem necessitates innovations in fertilizer formulation that can control the rate of nutrient availability to better match the physiological needs of plants throughout the growing season. Slow-release fertilizers (SRF) have emerged as a promising solution. This type of fertilizer is designed to extend the duration of nitrogen release, thereby improving nitrogen uptake efficiency while minimizing adverse environmental impacts. SRF technology has been extensively developed to gradually release nutrients, enhancing fertilizer use efficiency and reducing pollution risks, particularly in soil environments (Brown & Lee, 2023).

As a dynamic system, soil undergoes continuous changes that can be improved through fertilization. Fertilizer efficiency can be enhanced by incorporating carriers that regulate nutrient release. Research by Salman and Suntari (2023), using cassava starch (Manihot esculenta Crantz)-based carriers, demonstrated favorable results by prolonging nutrient release duration. Cassava starch was chosen as the carrier material due to its biodegradability and natural abundance. It is a complex polysaccharide composed of two primary molecules, amylose and amylopectin, that can form gels capable of encapsulating urea (Fitriany et al., 2023).

Previous studies by Salman and Suntari (2023) utilized cassava starch in capsule form as an SRF carrier. However, such capsules were prone to physical damage, including cracking and breaking. To overcome this limitation, the present study developed cassava starch -based bioplastics as SRF carriers for urea. The bioplastics were fabricated in sheet form to allow practical application and potential use as sustainable materials, such as polybags. This bioplastic carrier is expected to address the weaknesses of capsule-based carriers.

The production of bioplastics requires not only starch but also a plasticizer to impart elasticity and mechanical strength. Plasticizers function to reduce brittleness, increase flexibility, and enhance film durability, particularly under low-temperature storage conditions. In this study, glycerol was used as a plasticizer. Due to its low molecular weight, glycerol effectively increases film elasticity by expanding intermolecular spaces, thereby reducing rigidity and improving flexibility (Afifah et al., 2018). Andiati et al. (2022) further demonstrate that glycerol concentration influences solubility, water absorption, and tensile strength in edible films.

In addition to glycerol, polyvinyl alcohol (PVA) was employed to improve film-forming ability and plastic properties. According to Limbong et al. (2022), the incorporation of PVA significantly affects tensile strength (11.83–29.47 MPa) and elasticity (268.21 ± 14.44 MPa). These findings suggest that cassava starch-based bioplastics have significant potential for reducing fertilization frequency, improving nutrient use efficiency, promoting healthier plant growth, and enhancing environmental sustainability by minimizing pollution.

Research Method

The equipment used in this study included: stirring rods, vial bottles, Erlenmeyer flasks, a blender, a Universal Testing Machine (UTM), measuring cylinders, a hot plate, a magnetic stirrer, volumetric pipettes, volumetric flasks, a percolator apparatus, a UV-Vis spectrophotometer (Shimadzu 1280), centrifugal tubes, and a Fourier Transform Infrared (FTIR) spectrometer (Shimadzu IRPrestige 21).

The materials used included distilled water (DW), acetic acid, p-dimethylamino-benzaldehyde (PDAB, KGAa), glycerol (KGAa), hydrochloric acid (HCl 38%), phenolphthalein indicator (PP), polyvinyl alcohol (PVA, Schuchardt OHG 85662 Hohenbrunn, Germany), and urea fertilizer (PT Pupuk Indonesia Holding Company, PIHC).

Experimental Procedures

1. Cassava Starch Preparation

One kilogram of cassava was peeled, cut into small pieces, and blended with distilled water until a fine slurry was obtained. The slurry was then filtered using a polymicro cloth (70 g/m^2). The filtrate was allowed to settle for 24 hours, after which the supernatant was removed, leaving wet starch at the bottom. The wet starch was oven-dried at 50°C for 12 hours, then ground using a mortar and pestle into a fine powder. This powder was subsequently used as the primary material for bioplastic fabrication and for FTIR and fertilizer release testing (Natalia & Muryeti, 2020).

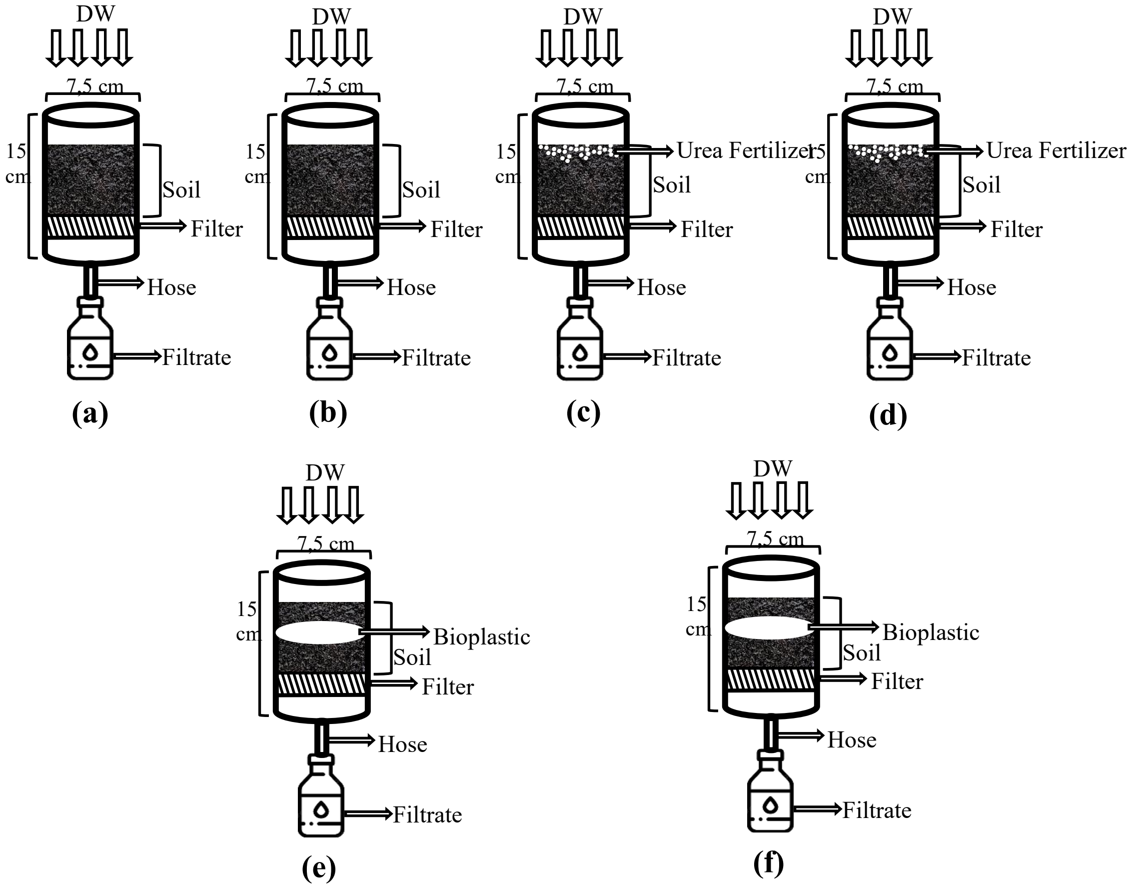

Figure 1. Percolator setup for SRF and degradation tests: (a) and (b) soil controls, (c) and (d) pure urea, (e) and (f) urea-based bioplastic

2. Preparation of Bioplastic

Bioplastic production was carried out in several stages. A PVA solution was first prepared by dissolving 2.5 g of PVA in 25 mL of hot distilled water (90°C). Separately, 2.5 g of cassava starch was dissolved in 25 mL of distilled water, and 2.5 g of urea fertilizer was dissolved in 10 mL of distilled water. The starch solution was mixed with the PVA solution and stirred on a hot plate at 90°C until the mixture thickened. The hot plate was then turned off, and the mixture was allowed to cool to room temperature. Glycerol and the urea solution were added to the cooled mixture and stirred until the mixture was homogeneous. The resulting viscous solution was poured into an acrylic mold

(21 cm × 14 cm × 2 mm) and oven-dried at 50°C for 20 hours. Bioplastic samples containing urea were labeled as BP, while control samples without urea were labeled as BP0. After drying, the bioplastics were removed from the molds and subjected to mechanical, water absorption, and nitrogen content analyses (Nugroho et al., 2019).

3. Water Absorption Test (Water Uptake)

The initial dry weight of the sample (W_0) was recorded. Each sample was immersed in distilled water for 10 seconds, removed, and weighed (W). This immersion and weighing process was repeated three times until a constant weight was obtained. The percentage of absorbed water was calculated using the following equation (Darni & Utami, 2009):

$$\text{Water uptake } (\%) = \frac{W - W_0}{W_0} \text{ x } 100$$

Notes:
W_0 = dry weight of the sample
W = weight of the sample after immersion

4. Mechanical Testing

Mechanical properties were measured using a UTM to determine:

a. Tensile strength
b. Elongation at break (elastic modulus)

5. Functional Group Analysis using Fourier Transform Infrared

FTIR spectroscopy was performed to analyze and compare the functional group characteristics of urea-containing bioplastics (BP) and urea-free bioplastics (BP0).

6. Slow-Release Fertilizer Test

The bioplastic samples used in this test were composed of cassava starch, PVA, glycerol, and urea. Each bioplastic sheet was cut into a uniform size of 9.5 cm × 6 cm and buried in soil at a depth of 5 cm from the surface. As controls, pure urea (conventional urea without any additional materials) and plain soil without any bioplastic were used to ensure the accuracy of nutrient-release measurements. The percolator setup was arranged as illustrated in **Figure 1**, showing the placement of each sample and the measuring instruments used in the SRF test. Distilled water (aquadest) was added to each percolator until the soil and sample were fully moistened to maintain a consistent level of humidity throughout the experiment. Water samples (percolates) were collected daily for six days, with 15 mL taken from each percolator at every sampling for further analysis.

The SRF analysis employed PDAB as the colorimetric reagent. The PDAB solution was prepared by dissolving 2.5 g of PDAB in 50 mL of ethanol, adding 2.5 mL of sulfuric acid, and diluting the mixture with distilled water to a final volume of 100 mL, yielding a 167.5 mM solution. This stock solution was further diluted to 20 mM by mixing 6 mL of the stock PDAB solution with 50 mL of distilled water. The diluted reagent was stored in a brown glass reagent bottle and remained stable for up to nine days. For each daily sampling, 15 mL of percolate was collected from each percolator, centrifuged, and filtered. To the clear filtrate, 2.5 mL of PDAB reagent and 0.5 mL of HCl were added. The mixture was allowed to stand for 10 minutes to allow color development, after which the absorbance was measured using a UV-Vis spectrophotometer (Shimadzu 1280). Measurements were performed daily throughout the six-day observation period (Fitriany et al., 2023). Biodegradation observations were conducted on day 6 to examine morphological changes in the bioplastic samples. The degree of degradation was determined gravimetrically by weighing the bioplastic samples before and after the six-day process. The biodegradation efficiency was calculated using the following formula:

$$\text{Efficiency } (\%) = \frac{(U-T)-(B-T)}{(U-T)}$$

Notes:
U = urea (control)
T = soil
B = bioplastic sample

Results and Discussion

1. Cassava Starch Preparation

Cassava starch was prepared by processing 1 kg of thoroughly cleaned cassava tubers, which were cut into small pieces to facilitate homogenization. The pieces were blended with distilled water (aquadest) to improve grinding efficiency and accelerate cell disruption. The resulting slurry was filtered and pressed to separate the starch-containing liquid from fibrous residues. The filtrate was then allowed to settle for 24 hours. After sedimentation, the supernatant was discarded, leaving the wet starch at the bottom of the container. This wet starch was subsequently dried in an oven at 90°C to reduce its moisture content and obtain dry starch powder.

The drying process yielded 289.1 g of cassava starch with a recovery rate of 28.9%. This value is higher than the 15.54% yield reported by Atifah et al., indicating that the cassava processing method used in this study was effective in producing high-quality starch with superior yield. Generally, good-quality cassava starch yields range between 20% and 30% of the fresh tuber weight, with yields above 25% considered optimal. The starch quality and yield are strongly influenced by the cassava variety, as each cultivar contains different starch concentrations. Certain varieties naturally possess higher starch content, which contributes to greater extraction efficiency and yield (Natalia & Muryeti, 2020).

2. Preparation of Bioplastic

Bioplastic films were produced in two formulations: one containing fertilizer (BP) and one without fertilizer (BP0), as shown in **Figure 2**. The production process involved dissolving PVA in distilled water at 90°C to form a homogeneous solution. Efficient heating enhanced molecular motion and water penetration into PVA, thereby promoting dissolution (Widyaningrum et al., 2020). Due to its hydrophilic nature and excellent film-forming capability, PVA served as an optimal polymer matrix. The heating step also facilitated gelatinization of cassava starch, increasing the viscosity and stability of the mixture.

Uniform stirring of starch and PVA, followed by the addition of glycerol as a plasticizer, improved the flexibility and tensile strength of the resulting bioplastic. Urea was incorporated as an SRF component, which decomposed into isocyanic acid and ammonia ($CH_4N_2O \rightarrow CHNO + NH_3$). The viscous mixture was then cast into molds and dried at 50°C for 20 hours to ensure even water evaporation. The films were subsequently conditioned for 72 hours to achieve optimal thermal stability and mechanical strength (Nugroho et al., 2019).

The resulting bioplastic exhibited a clear, smooth, elastic, and flexible texture, with excellent biodegradability. The film thickness was approximately 0.09 mm, with a length of 19 cm and a width of 12 cm. These characteristics indicate that the chosen formulation and fabrication process were effective in producing high-quality cassava-based bioplastics suitable for further application as SRF carriers.

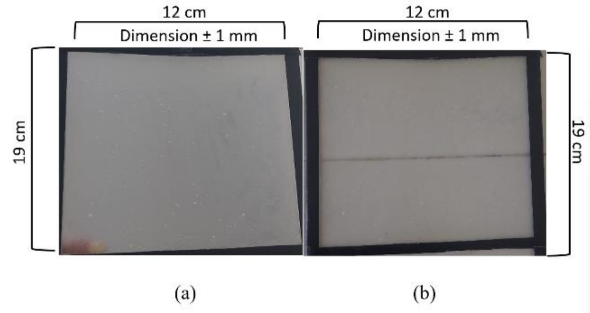

Figure 2. (a) Bioplastic containing fertilizer (BP) and (b) Bioplastic without fertilizer (BP0).

3. Water Uptake Test

The water uptake test revealed that both bioplastics, BP and BP0, exhibited notable water absorption capacities. The weight of BP increased from 1.8400 g to 3.3866 g, while BP0 increased from 1.8602 g to 3.3614 g. The water resistance of BP was

Tabel 1. Results of Tensile Strength and Elongation at Break Tests

No.	Bioplastic	Tensile Strength (MPa)	Elongation at Break (%)	SNI ISO 527-1:2016 Standard	
				Tensile Strength (MPa)	Elongation at Break (%)
1.	BP	0.50	125.7	24.7-302	21-220
2.	BP 0	0.99	137.8		

recorded at 73.45%, which was higher than that of BP0 at 67.44% (see **Figure 3**). These results indicate that BP possessed a higher water absorption capacity, reflecting the influence of fertilizer content on the hydrophilic properties of the bioplastic. However, neither sample met the Indonesian National Standard (SNI ISO 527-1:2016), which specifies a water resistance value of up to 99%.

The incorporation of glycerol and PVA contributed to improved water absorption and flexibility. Glycerol, acting as a plasticizer, increases the porosity of the polymer structure, thereby facilitating water penetration (Maneking et al., 2020). PVA, with its hydrophilic nature, enhances intermolecular interactions among biopolymer chains, improving both elasticity and water uptake (Widyaningrum et al., 2020). Additionally, urea, being hygroscopic, absorbs moisture from the environment through hydrogen bonding, which consequently increases the humidity and potential degradation rate of the bioplastic under moist conditions (Nailah & Millisa, 2023). Overall, the combination of these components improved the balance between flexibility and water absorption, supporting the overall functional quality of the cassava-based bioplastic.

4. Mechanical Properties: Tensile Strength and Elongation at Break

Tensile strength represents a key mechanical property of biodegradable bioplastics, defined as the maximum stress the material can withstand before failure. This test determines the force required to stretch or elongate the film until it breaks. Variations in mechanical properties primarily arise from the addition of plasticizers, which weaken the intermolecular forces between polymer chains.

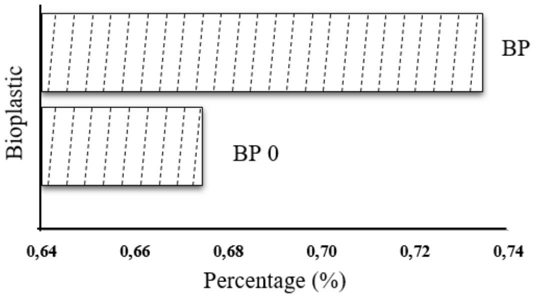

Figure 3. Comparison of (a) BP (bioplastic with fertilizer) and (b) BP0 (bioplastic without fertilizer).

The results of the tensile strength and elongation at break tests demonstrated that BP exhibited a tensile strength of 0.50 MPa, whereas BP0 achieved 0.99 MPa. These findings suggest that the incorporation of fertilizer has a significant impact on the mechanical behavior of the bioplastic, particularly its tensile strength and elongation capacity. The lower tensile strength of BP compared to BP0 suggests that the addition of urea tends to weaken the polymer matrix. The hygroscopic nature of urea contributed to this reduction by absorbing moisture from the surrounding environment, thereby disrupting hydrogen bonding between polymer chains and decreasing the overall cohesion of the bioplastic network. Consequently, the material became less flexible and less capable of withstanding mechanical stress. Despite the variations observed, neither formulation fully met the SNI ISO 527-1:2016 standard requirements for tensile strength and elongation (see **Table 1**) (Melani et al., 2022).

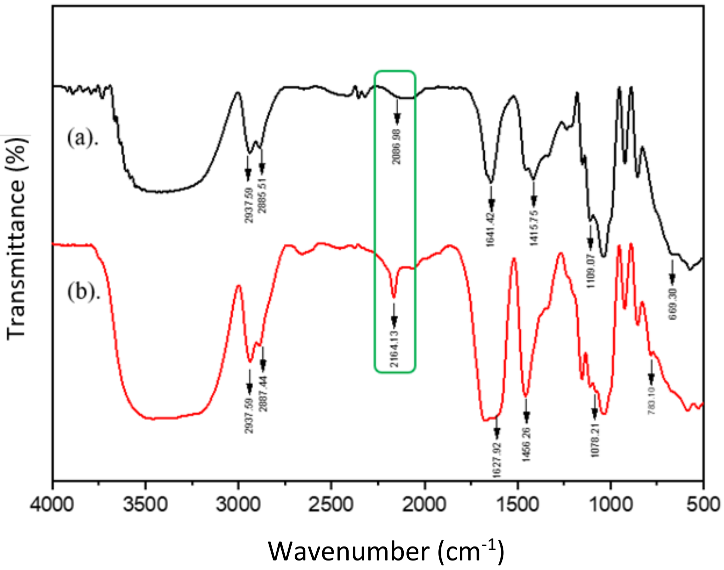

Figure 4. FTIR spectra of (a) BP0 (bioplastic without fertilizer) and (b) BP (bioplastic with fertilizer).

5. Functional Group Analysis Using Fourier Transform Infrared

FTIR spectroscopy was employed to identify functional groups and chemical bonds within the bioplastic samples. This analysis aimed to examine the composition and structural modifications of bioplastics composed of distilled water, PVA, glycerol, and urea, with and without the addition of fertilizer. Through the FTIR spectrum, distinct absorption peaks were observed, revealing the types and bonding environments of the chemical constituents. This enabled evaluation of the molecular interactions among the components and the structural effects of fertilizer incorporation. A new peak was observed in the bioplastic containing urea, indicating an interaction between urea and PVA (see **Figure 4**), which is consistent with the FTIR profile of pure urea (Widyaningrum et al., 2020).

The FTIR results of the bioplastics exhibited several significant peaks corresponding to specific chemical bonds. At 3439.08 cm^{-1} and 3383.14 cm^{-1}, absorption bands were identified, representing N–H stretching vibrations, which were present in both BP0 and BP spectra. This finding suggests the presence of primary amine or amide groups within the molecular structure (Saputra & Supriyo, 2022). The N–H groups likely originate from primary amines (–NH_2) or amides (–$CONH_2$), typically found in compounds containing amino functionalities, such as protein-based or polyurethane-like polymers. Furthermore, peaks observed at 2937.59 cm^{-1} and 2887.51 cm^{-1} correspond to C–H stretching vibrations, typically associated with alkyl groups in the polymer backbone. There were no significant differences between BP0 and BP spectra in these regions, indicating the stability of C–H bonds regardless of fertilizer addition.

The FTIR spectrum showing a peak at 2164.13 cm^{-1} indicates the presence of an isocyanate group (N=C=O). Although this functional group typically appears in the range of 2250–2275 cm^{-1}, the observed shift to a lower wavenumber suggests an interaction between the isocyanate group and hydroxyl (-OH) groups present in the sample. Such interactions can weaken the N=C=O bond strength, resulting in a lower stretching vibration frequency. Isocyanate groups are known for their high reactivity, particularly toward water and hydroxyl groups. In the analyzed FTIR spectra, several additional absorption peaks were identified, each representing distinct functional groups within the bioplastic compound. The peak at 1641.42 cm^{-1} in BP0 and 1627.92 cm^{-1} in BP corresponds to

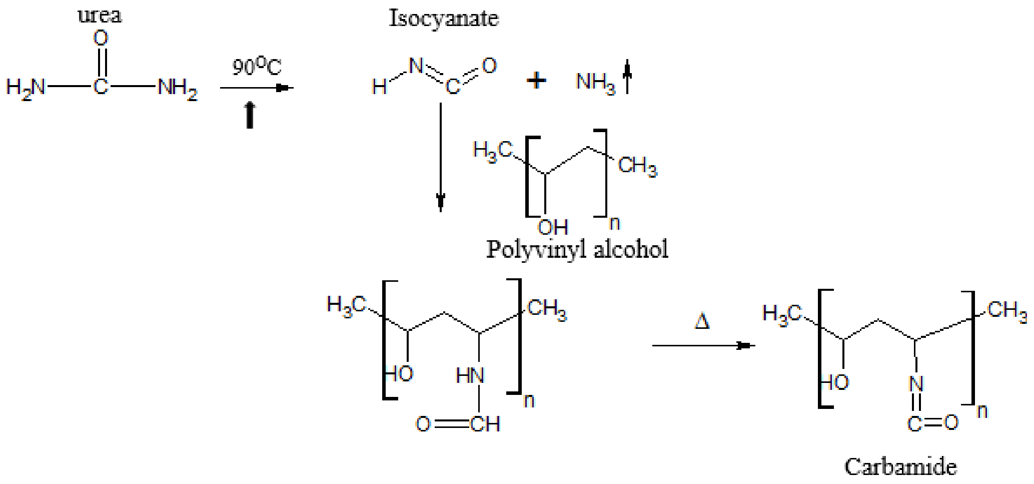

Figure 5. Interaction between Urea and PVA (Lei et al., 2009).

C=C double bonds, typically found in alkenes or aromatic structures. The slight frequency shift between the two samples suggests minor alterations in the chemical environment affecting bond length and strength. The consistent peak at 1456.26 cm^{-1} in both BP0 and BP indicates the presence of a nitro (-C–NO_2) group, which is relatively stable within the polymer matrix. Meanwhile, peaks at 1109.07 cm^{-1} (BP0) and 1078.21 cm^{-1} (BP) represent C–O–C stretching vibrations, characteristic of ether groups.

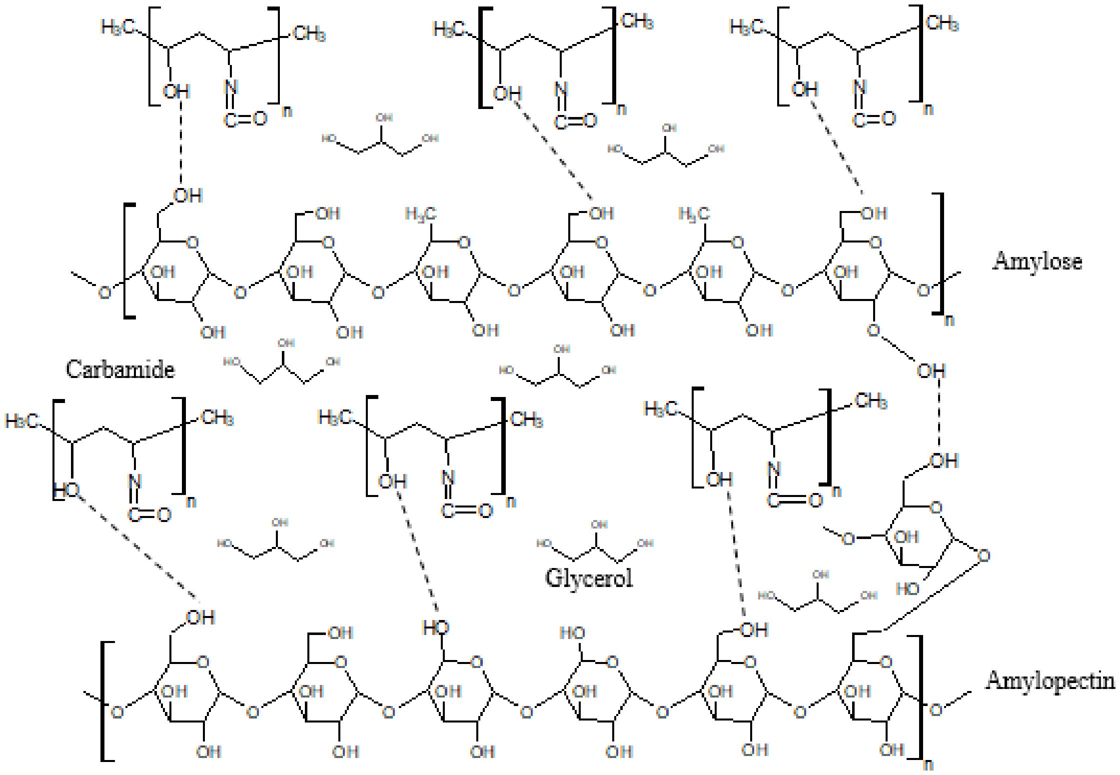

Figure 6. Proposed structural model of cassava-based bioplastic.

These small shifts likely reflect structural rearrangements or molecular interactions among polymer components. Finally, peaks at 669.30 cm^{-1} (BP0) and 783.10 cm^{-1} (BP) correspond to $-(CH_2)_n$ stretching vibrations, typically associated with alkyl chain segments. The notable frequency shift between the two suggests modifications in alkyl chain ordering or intermolecular interactions affecting CH_2 vibrational patterns (Hayati et al., 2020). Overall, the FTIR analysis demonstrates that the incorporation of fertilizer induced chemical structure modifications within the bioplastic matrix, evidenced by the appearance of a new isocyanate peak at 2164.13 cm^{-1}, which was absent in BP0. These changes likely resulted from chemical reactions between fertilizer components and the bioplastic matrix, altering the type and environment of chemical bonds within the material.

The emergence of the new peak at 2164.13 cm^{-1} signifies covalent bonding interactions between the isocyanate group (N=C=O) and PVA (see **Figure 5**). Beyond covalent and hydrogen bonds, van der Waals forces also played a role in maintaining the structural stability of the bioplastic, particularly in the interactions between starch and PVA polymer chains. The spectral shift from 669.30 cm^{-1} to 783.10 cm^{-1} further supported rearrangements in the alkyl chain conformation due to these molecular interactions. Collectively, the combination of hydrogen bonding, covalent linkages, and van der Waals forces indicates substantial structural reorganization following fertilizer addition, which may directly influence the physical and mechanical behavior of the resulting bioplastic.

Starch provided the main polymeric backbone through its amylose and amylopectin chains, functioning as the primary matrix. Glycerol, though not chemically bonded, acted as a plasticizing agent interspersed within the matrix, reducing intermolecular attraction and enhancing elasticity. This molecular spacing effect enabled the bioplastic to stretch and flex without fracturing, consistent with the functional role of plasticizers. Hydrogen bonds in the bioplastic were formed through interactions between isocyanate-modified PVA hydroxyl groups and hydroxyl groups from starch. The dominant intermolecular forces within the bioplastic network were hydrogen bonds, particularly between hydroxyl (-OH) groups of starch, PVA, and glycerol, and carbonyl (-C=O) and amine ($-NH_2$) groups from urea. This was evidenced by the characteristic N–H stretching bands at 3439.08 cm^{-1} and 3383.14 cm^{-1}, indicating strong interactions between urea and other bioplastic components. The high electronegativity of oxygen atoms within hydroxyl groups caused electron withdrawal from the O–H bond, giving the hydrogen atom a partial positive charge. Concurrently, the oxygen atom possessed a lone pair of electrons not engaged in covalent bonding. The electrostatic attraction between the positively charged hydrogen atom of one hydroxyl group and the lone pair of another oxygen atom formed hydrogen bonds, a key contributor to the structural integrity of the bioplastic (see **Figure 6**).

6. Slow-Release Fertilizer Test

The biodegradation and SRF test were conducted using a percolator apparatus, operating based on the principle of liquid filtration and percolation through a relevant soil medium (see **Figure 7**).

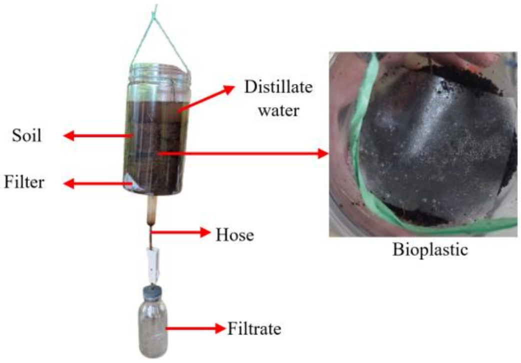

Figure 7. Percolator apparatus setup

The biodegradation test involved placing bioplastic samples inside a percolator column filled with water-saturated peat soil, simulating natural soil conditions. During the test, water was allowed to flow through the percolator, passing over the bioplastic samples and urea fertilizer to simulate rainfall and monitor the release of nutrients into the leachate. The results of the urea release test (see Figure 8) demonstrated a more gradual release pattern in the bioplastic-encapsulated fertilizer compared to conventional urea. Over the observation period, bioplastics containing urea released nutrients slowly and consistently, achieving a release efficiency of approximately 66%. In contrast, conventional urea dissolved rapidly in water, resulting in a burst release and increasing the risk of leaching losses and nutrient inefficiency. In terms of physical degradation, BP1 (initial weight 2.86 g) decreased to 2.01 g, and BP2 (initial weight 3.08 g) decreased to 2.07 g by the end of the testing period, representing an average mass loss of around 31%. This mass reduction indicates significant biodegradation, suggesting that the bioplastic material decomposes effectively under soil conditions, a desirable feature for environmentally friendly fertilizer carriers.

The degradation process was influenced by the hygroscopic nature of urea, which promotes the absorption of moisture into the polymer matrix, thereby weakening intermolecular bonds and reducing the mechanical stability of the bioplastic (Intandiana et al., 2019). Nutrient concentration measurements were performed using a UV–Vis spectrophotometer, where the standard urea solution was scanned to determine its maximum absorption wavelength at 414 nm. During analysis, the PDAB reagent was used to form a colored complex with urea, allowing for quantitative detection through spectrophotometry. The wavelength of 414 nm was chosen because urea exhibits maximum light absorption in this range, enabling high sensitivity and precision in detecting even slight concentration changes. Moreover, this wavelength minimizes interference from other compounds, as most do not absorb strongly at this frequency (Abriyani et al., 2024).

From the release profile curve, it can be inferred that bioplastic-based SRF systems are more effective at controlling urea release compared to conventional fertilizers. The 66% efficiency data support that bioplastics can enhance fertilizer utilization, minimize nutrient loss through leaching, and mitigate negative environmental impacts. Hence, cassava-based bioplastics represent a superior alternative to conventional urea, particularly for maintaining soil ecosystem balance and improving nutrient-use efficiency in agricultural systems.

The test results also confirmed that the bioplastic enabled gradual and sustained urea release, owing to the incorporation of PVA, glycerol, and starch, which collectively functioned as structural stabilizers and release modulators. PVA contributes to maintaining matrix stability under varying soil moisture levels, while glycerol enhances flexibility and moisture retention, both of which are crucial for consistent nutrient delivery (Prastika, 2023; Habibi et al., 2023). Starch acts as a filler and biodegradation enhancer, facilitating hydrolysis and regulating nutrient diffusion through the polymer structure.

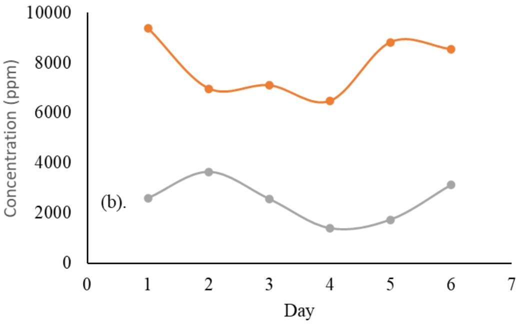

Figure 8. SRF release test results: (a) Conventional urea and (b) Bioplastic (BP).

During the urea release test, the bioplastic samples exhibited slower and more controlled nutrient release compared to uncoated urea. This behavior results from the gradual degradation mechanism of the bioplastic, in which nutrients are released progressively as the matrix decomposes. Unlike conventional urea, which dissolves instantaneously, the bioplastic ensures sustained nutrient availability over time.

Consequently, cassava-based bioplastics not only meet the technical requirements for SRF applications but also align with global efforts to reduce the environmental footprint of conventional plastics. The bioplastic samples tested in this study demonstrate strong potential for improving fertilizer efficiency, reducing nutrient loss, and enhancing soil quality by maintaining soil ecosystem stability and minimizing the risk of contamination from nutrient runoff (Hartatik, 2020).

Conclusion

Both types of bioplastics exhibited smooth, transparent, elastic, and flexible characteristics, as well as biodegradability. The urea-loaded bioplastic (BP) demonstrated a tensile strength of 0.50 MPa, whereas the urea-free bioplastic (BP 0) showed a higher tensile strength of 0.99 MPa. In terms of water resistance, BP exhibited a durability of 73.45%, while BP 0 recorded 67.44%. The FTIR analysis indicated a change in the chemical structure of the bioplastic, as evidenced by the shift in absorption peak at 2164.13 cm^{-1}. During the biodegradation process, the bioplastic degraded by approximately 31% within six days. The biodegradation test confirmed that the urea-based bioplastic could effectively decompose in soil environments, demonstrating its potential as an eco-friendly plastic alternative. Moreover, the SRF test demonstrated that the bioplastic effectively carried urea, achieving a nutrient-release efficiency of 66%, which outperformed the non-carrier control.

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