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Study of the Structural Property and Biodegradation Relationship of Regenerated Cellulose Nanofibre/Glycerol Laminated Films Incorporating Recycled PLA Waste

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ABSTRACT

The increasing generation of plastic waste from packaging and additive manufacturing, particularly polylactic acid (PLA), necessitates sustainable recycling strategies. This study reports the fabrication of regenerated cellulose nanofibre (RCNF) composite films incorporating recycled PLA waste from 3D printing and glycerol as a plasticiser for sustainable packaging applications. Cellulose nanofibres were dissolved using a sodium hydroxide-urea (NaOH/urea) solvent system and regenerated via a freeze–thaw process, followed by chloroform-dissolved PLA waste phase and lamination with a glycerol-containing coagulants at varying concentrations. The structural properties of the fabricated RCNF/glycerol/PLA films were thoroughly analysed. The

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Fourier Transform Infrared Spectroscopy (FTIR) analysis demonstrated the existence of intermolecular interactions among cellulose, glycerol, and PLA. Concurrently, the higher glycerol content has enhanced the flexibility and water uptake of the film produced, reaching over 300% at 20% glycerol loading. However, the incorporation of PLA into the film composite has reduced water absorption due to the polymer cellulose chain entanglement. Meanwhile, the soil burial tests revealed that higher glycerol concentrations slowed biodegradation by reduction of the weight loss. In contrast, the increase in the incubation temperatures has intensified the weight loss where 50 °C incubation demonstrated higher weight loss percentage. However, these films showed increased thermal decomposition, suggesting enhanced processability under heat. The findings highlight the potential of upcycled CNF/PLA/glycerol films as an environmentally friendly alternative for packaging applications, contributing to circular material use and reduced ecological impact.

1. INTRODUCTION

The extensive use of petroleum-based plastics in packaging and everyday products has created serious environmental problems because these plastics do not break down easily and tend to build up in the landfills and the natural environment [1-3]. Current reports reveal that fewer than 10% of plastic wastes are successfully recycled, while most end up in landfills or leak into the natural environment, where it can persist for centuries. Despite their better mechanical properties and low cost, this is particularly evident in the case of soft plastics such as polyethylene bags, which remain one of the most problematic waste streams globally [4-5]. Hence, these problems have increased global interest in finding sustainable, biodegradable alternatives derived from renewable resources.

Cellulose is a long-chain polymer of glucose molecules joined together, possessing biodegradability, and recognized as a highly sustainable and renewable material with emerging innovative applications [6-9]. Cellulose is derived from various biomass sources, such as agricultural residues like oil palm empty fruit bunches, kenaf, and other plant materials. When cellulose is processed through dissolution and regeneration, it can be transformed into regenerated cellulose films that are widely used in packaging, membranes, and biomedical fields [9-11]. Despite their potential, regenerated cellulose films tend to be brittle, not very flexible, and less resistant to heat, which makes them difficult to use in a wider range of applications.

Through plasticization techniques, particularly the use of polyols like glycerol, are widely used to enhance the flexibility and ductility of cellulose-based films by disrupting the strong hydrogen bonding between cellulose chains. Although glycerol helps to enhance flexibility and increase water uptake, however, its excessive use can reduce dimensional stability and durability, highlighting the need for careful control of composition. As a result, blending regenerated cellulose with polymers that provide reinforcement or act as barriers has become a promising alternative to address these limitations [12-14].

In addition, additive manufacturing technologies have grown rapidly, particularly in fused deposition modelling (FDM). The technological demand has emerged in a significant increase in polylactic acid (PLA) waste generated from failed prints, support structures, and discarded prototypes [15-18]. PLA is a bio-based and biodegradable polymer widely used in 3D printing; however, repeated thermal processing during recycling can degrade its mechanical and thermal properties [17, 19-22]. Despite the increasing research on regenerated cellulose films and recycled PLA, few studies have considered at combining regenerated cellulose nanofibres, plasticisers, and recycled PLA waste into a single composite especially using solvent-assisted processing methods. In addition, the effect of plasticisers on water absorption and the biodegradation of cellulose-PLA composite films is still not well understood. Therefore, filling this gap is crucial for developing biodegradable packaging that combines flexibility, durability, and environmental stability.

Recent research has explored recycling PLA waste from additive manufacturing through mechanically reprocessing, re-extrusion, or blending with natural fillers to enhance sustainability [16-17]. Concurrently, research has investigated regenerated cellulose-based films, plasticised with glycerol or combined with synthetic polymers, to enhance their flexibility and water absorption characteristics [12, 23]. However, these approaches typically treat recycled PLA and regenerated cellulose as separate material streams or depend on melt compounding, which can cause thermal degradation and reduce interfacial compatibility. In contrast, this study presents a solvent-assisted lamination approach that combines regenerated cellulose nanofibres, glycerol, and post-consumer 3D-printed PLA waste (recycled PLA) into a single composite film, allowing better control over the interactions between the hydrophilic cellulose and hydrophobic PLA phases [24]. Therefore, combining structural property analysis with soil burial degradation studies can offer new insights into how plasticiser content and PLA incorporation together influence flexibility, swelling behavior, and degradation rate, highlighting a practical approach to upcycling additive manufacturing waste into biodegradable packaging within a circular materials framework [17, 20, 22].

Therefore, this study aims to develop regenerated cellulose nanofibre (RCNF) composite films incorporating glycerol as a plasticiser and recycled PLA waste from 3D printing via a solvent-assisted lamination strategy. The physicochemical properties of the resulting films were systematically investigated through Fourier transform infrared spectroscopy, water uptake kinetics, qualitative mechanical evaluation, and soil burial biodegradation testing. This work provides new insights into the synergistic effects of glycerol and recycled PLA on the performance and degradation behaviour of cellulose-based composite films, contributing to the upcycling of additive manufacturing waste within a circular materials framework.

2. EXPERIMENTAL METHODOLOGY

2.1 Materials

Sulphuric acid (96%, R&M Chemicals), sodium hydroxide (NaOH) pellets (R&M Chemicals), and NaOH pellets (Bendosen) were used in the preparation of regenerated cellulose nanofibre (RCNF). Urea (HmBG Chemicals), chloroform, and cellulose nanofibre (CNF) extracted from oil palm empty fruit bunch (ZoepNano) were employed for cellulose dissolution. Glycerol was obtained from EMC Technology, while fragments of 3D-printed products were collected as the source of PLA, which were shredded to sizes ranging from 0.1 to 0.5 cm. The soil used in the experiment was purchased from a local store.

2.2 Preparation of Regenerated Cellulose Film

The weight of 7% NaOH and 12% urea were measured and prepared, consequently were dissolved in the CNF solution of 2 wt %. The mixed solutions were then stored in a freezer at temperature of −20 °C. The frozen solvent was subsequently melted until it reached temperature of −13 °C and stirred until a

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cellulose solution was formed. The formed cellulose solution was cast onto a glass plate and then subsequently soaked into the designated coagulation bath to form regenerated cellulose films.

2.3 Preparation of PLA and Glycerol Coagulant

The weight of the shredded PLA waste from the 3D printing process was measured, and the shredded PLA was stirred in chloroform to dissolve the PLA, resulting in a 5 wt % PLA solution. The solution was then stored in a refrigerator at 5 °C prior to use. Meanwhile, several glycerol solutions of different concentrations (2.5%, 5.0%, 10.0%, and 20.0% v/v) were prepared. The glycerol solutions were used as coagulants and acted as plasticisers for the RCNF formation. Glycerol/PLA coagulants were also prepared by mixing each glycerol solution with the previously prepared 5% PLA solution. The samples type and its coagulant was summarized in Table 1.

Table 1: Samples and Type of Coagulants Used in the Lamination Process

Samples	**Coagulant**
RCNF	5% H_2SO_4
RCNF-2.5%Glycerol	2.5% Glycerol
RCNF-5.0%Glycerol	5.0% Glycerol
RCNF-10.0%Glycerol	10.0% Glycerol
RCNF-20.0%Glycerol	20.0% Glycerol
RCNF-5%Glycerol/5%PLA	5.0% Glycerol + 5.0% PLA

2.4 RCNF/Glycerol/PLA Lamination Composites

Composites of RCNF/glycerol and RCNF/glycerol/PLA were formed by coagulating cast cellulose solutions in the prepared coagulants. Subsequently, the composites were prepared for lamination by combining the cellulose solution with glycerol, followed by lamination with PLA via solvent casting. The resulting laminated composites were air-dried at room temperature until they turned into plastics. The schematic diagram of the samples preparations is shown in Fig. 1.

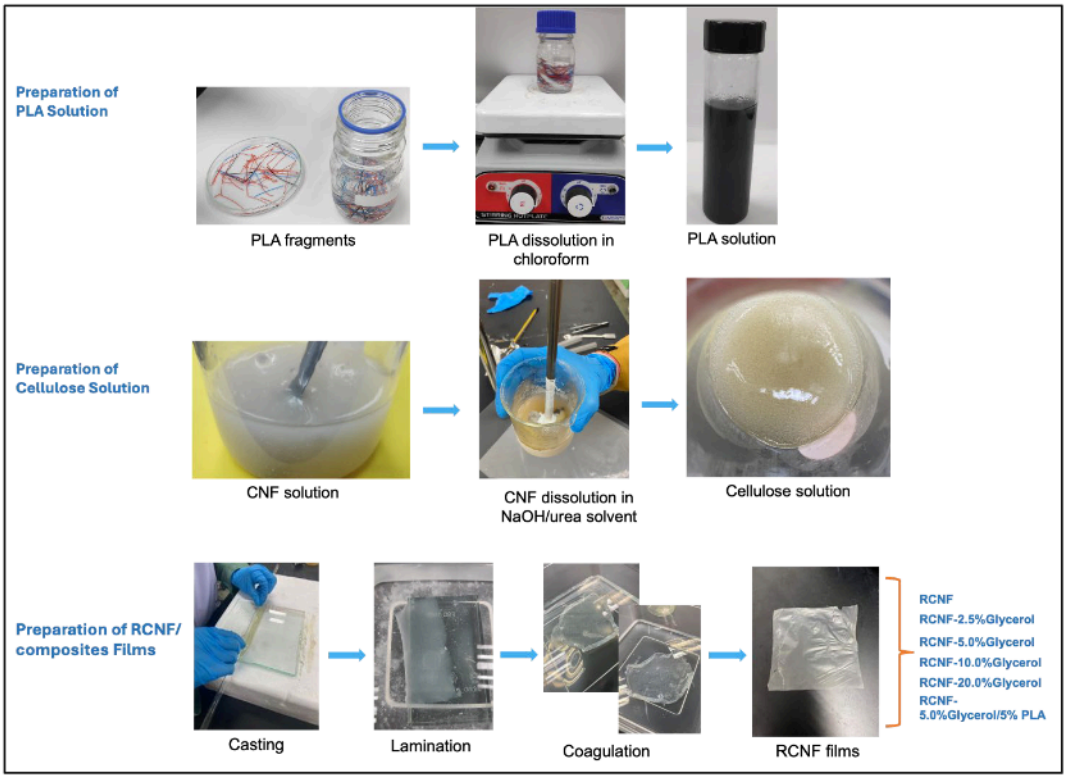

Fig. 1. Schematic diagram of the preparation of RCNF/composites films

2.5 Characterizations

The samples were physically characterised by assessing their surface roughness and transparency. Surface roughness was measured on both the top and bottom surfaces of each sample, while transparency was also evaluated. The mechanical properties of the films including tear strength, fragility, and foldability were examined. The tear strength was assessed by tearing the edge of each film and observing the tearing behaviour. Meanwhile, the flexibility was evaluated by folding the films to observe how easily they could bend and noting any cracking or breaking, which would indicate brittleness of the films.

The functional groups of CNF, RCNF/glycerol, and RCNF/glycerol/PLA composites were analysed using an attenuated total reflectance-Fourier transform infrared spectrometer (ALPHA; Bruker) with a resolution of 1 cm^{-1} in the wavenumber range of 4000 - 650 cm^{-1}.

The water uptake kinetics of all samples were calculated by immersing the films in distilled water at various time intervals until equilibrium was reached. Afterwards, the samples were removed from the water, dried with filter paper, and weighed. The percentage of water uptake was then calculated using Eq. (1).

$$WU(\%) = (W_{wet} - W_{dry})/W_{dry} \times 100\% \qquad (1)$$

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where *WU* is the water uptake, W_{wet} is the weight of the absorbed film, and W_{dry} is the weight of the dried film [25]. The kinetics of water adsorption data were fitted to the pseudo-second-order model [13], where q_e (g/g) and q_t (g/g) are the water absorbency of the product at equilibrium and time *t*, respectively. Meanwhile, k_2 (g·mg⁻¹·min⁻¹) is the rate constant of the pseudo-second-order model, as expressed in Eq. (2).

$$q_t = \frac{k_2 qe^2 t}{1 + \quad k_2 q_e t} \tag{2}$$

2.6 Biodegradation Process

The biodegradation process was conducted using potting mix soil as the incubation medium. Prior to use, the soil was air-dried and sieved to remove stones and debris, and a single homogeneous batch was used throughout the experiment. Film samples with a maximum size of 3 mm were buried in two separate plastic containers containing the prepared soil and incubated at two different temperatures of room temperature and 50 °C. Soil moisture was not quantitatively measured; however, it was periodically monitored and maintained under ambient conditions to prevent excessive drying, and no external humidity control was applied. All samples were maintained under identical burial conditions to ensure reliable comparative evaluation of biodegradation behaviour. At set intervals, the samples were collected, gently washed to remove any soil, and oven-dried at 50 °C until they reached a constant weight. The weight loss was then measured, and the biodegradation rate was calculated using Eq. (3) [24].

$$Weight\ loss\ (\%) = \frac{Wi - Wdry}{Wi} \tag{3}$$

where W_i is the initial weight of the sample before burial and W_{dry} is the dry weight of the sample after burial and subsequent drying in the oven.

3. RESULTS AND DISCUSSION

3.1 FTIR Analysis of RCNF/Composite Films

Fourier transform infrared (FTIR) spectroscopy is a common analytical technique used to study the molecular structure and chemical composition of materials. The infrared absorption between 4000 and 650 cm⁻¹ was measured in the transmittance mode, and the resulting FTIR spectra provide detailed information about the functional groups and bonding interactions within the sample. The width and intensity of peaks in FTIR spectra are significantly affected by the molecular structure and chemical environment of the macromolecules. When different polymers are mixed, interactions between them can occur, leading to noticeable changes in the FTIR spectra [26]. The FTIR analysis in Fig. 2(a) highlights the interactions between CNF (converted to RCNF) and the added glycerol and PLA during the lamination process. The CNF spectrum displayed a peak at 3250 cm⁻¹, corresponding to O–H stretching vibrations from both intra- and intermolecular hydrogen bonds. Meanwhile, a peak near 2930 cm⁻¹ is attributed to C–H stretching of methyl or methylene groups and the band at 1425 cm⁻¹ is associated with CH_2 bending modes. Additionally, the peaks at 1330 and 1084 cm⁻¹ correspond to C–O stretching vibrations. The band near 920 cm⁻¹ is associated with CH_2 groups, and the absorption at 840 cm⁻¹ is attributed to C–C bond stretching vibrations [23, 27]. The band at 2900 cm⁻¹ arises from interactions between glycerol and the CH_2 groups in CNF molecules. However, the characteristic PLA peak at 1766 cm⁻¹ is absent in the RCNF/Glycerol/PLA spectrum, likely due to the low concentration of PLA in the mixture.

Meanwhile, Fig. 2(b) demonstrated how glycerol content affects the interaction between RCNF and glycerol. The absorbance peak at 1653 cm⁻¹, corresponding to H–O–H bending, represents adsorbed water. The intensity of the band at 1644 cm⁻¹ increases as more glycerol is added [14,28]. A significant difference in peak intensity at 1650 cm⁻¹ corresponds to the H–O–H bending of water in glycerol. The changes in absorbance at different peaks with increasing glycerol content indicate interactions between cellulose and glycerol, suggesting that glycerol remains incorporated within the cellulose fibres during lamination [23]. The peak at 1057 cm⁻¹ in the glycerol-CNF spectrum is attributed to C–O–C stretching vibrations in the pyranose ring of aliphatic primary and secondary alcohols [23, 28 - 29] Additionally, the absorbance at 895 cm⁻¹ increases in films containing glycerol, with the intensity rising as the glycerol content increases. These interactions indicate that glycerol remains incorporated within the film during both the regeneration and lamination processes, showing that it is not removed during washing [23].

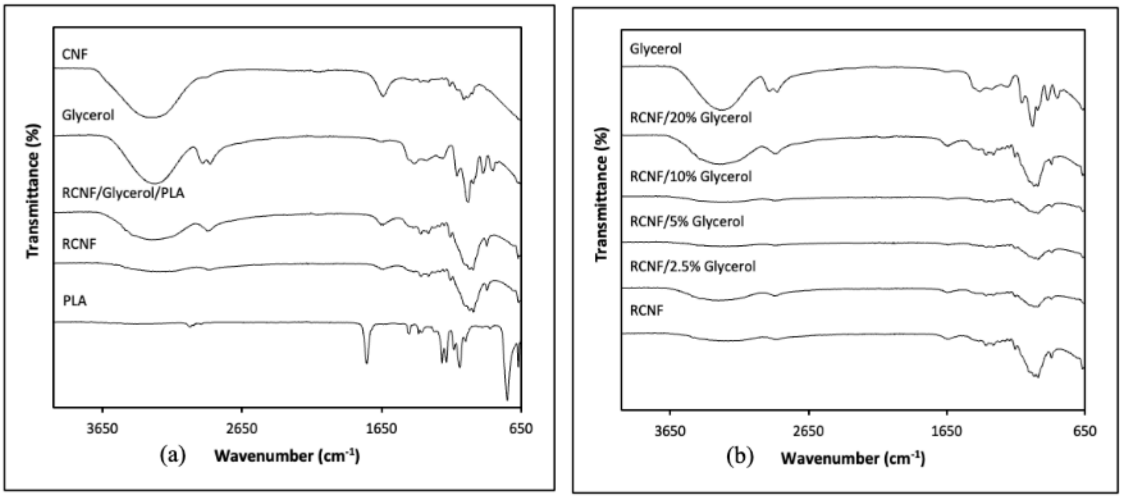

Fig. 2. FTIR spectra of (a) RCNF, glycerol and PLA and (b) the effect of glycerol content in RCNF films

3.2 Surface Roughness and Optical Transparency

The surface roughness and optical transparency of the regenerated cellulose nanofibre (RCNF), RCNF/glycerol, and RCNF/glycerol/recycled PLA laminated films were evaluated to assess the influence of plasticisation and lamination on physical appearance and surface uniformity. The physical properties of the produced RCNF samples that were coagulated in glycerol at different glycerol concentrations and subsequently mixed with PLA solution via the lamination method are shown in Fig. 3.

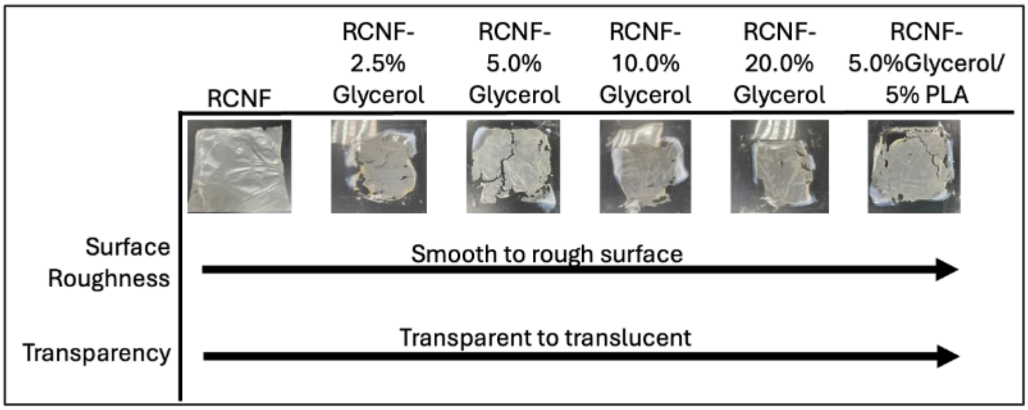

Fig. 3. Physical properties of RCNF interacted with different glycerol concentrations and PLA

Surface roughness was examined qualitatively using surface profile analysis to compare relative surface texture among the films. It is evident that the addition of glycerol and PLA influenced the surface roughness of the samples. Furthermore, higher glycerol concentrations increased the roughness of the top surface of the films, whereas the bottom surfaces, which contained the cellulose solution in contact with the surface of the glass plate, remained smooth. Meanwhile, the dissemination between the coagulants containing glycerol at different concentrations and the cellulose solution was prolonged for the bottom surface compared to the top surface, which was directly exposed to the coagulant. Therefore, rougher surfaces were observed at higher glycerol concentrations. In contrast, the laminated films with recycled PLA showed smoother surfaces, likely due to the formation of a continuous PLA layer that fills in surface irregularities and enhances overall uniformity [29].

Optical transparency was also evaluated qualitatively through visual inspection and photographic comparison of the films. The pure RCNF and glycerol-plasticised films exhibited reduced transparency due to increased light scattering associated with surface irregularities and internal microstructural heterogeneity. The films produced through lamination with glycerol and PLA exhibited lower transparency compared to RCNF films. During coagulation process, the cellulose solution comes into contact with the coagulant, triggering a solvent exchange in which the coagulant penetrates the cellulose while the original solvent (alkali and urea) diffuses outward [9]. Film transparency was found to depend on how well glycerol and PLA mix with water. The higher the glycerol content reduced miscibility, leading to a cloudy appearance on the film surfaces [9]. Additionally, light transmittance was affected by the different refractive indices of cellulose and the coagulant components. When light passes through the film, it can be transmitted, reflected, refracted, scattered, or absorbed, and the mismatch between cellulose and coagulant enhances light reflection, further reducing transparency during the lamination process [13].

3.3 Mechanical Properties of RCNF/Composite Films

The mechanical behaviour of the RCNF, RCNF/glycerol, and RCNF/glycerol/PLA films was qualitatively evaluated through foldability, tear resistance, and manual deformation to assess relative flexibility and structural integrity. During the foldability test, all films were cut into 2 ×2 cm pieces and folded to evaluate how well they could bend and how folding affected their structure. Based on the qualitative analysis, it indicates that all films could be folded easily, demonstrating their flexibility, as shown in Fig. 4.

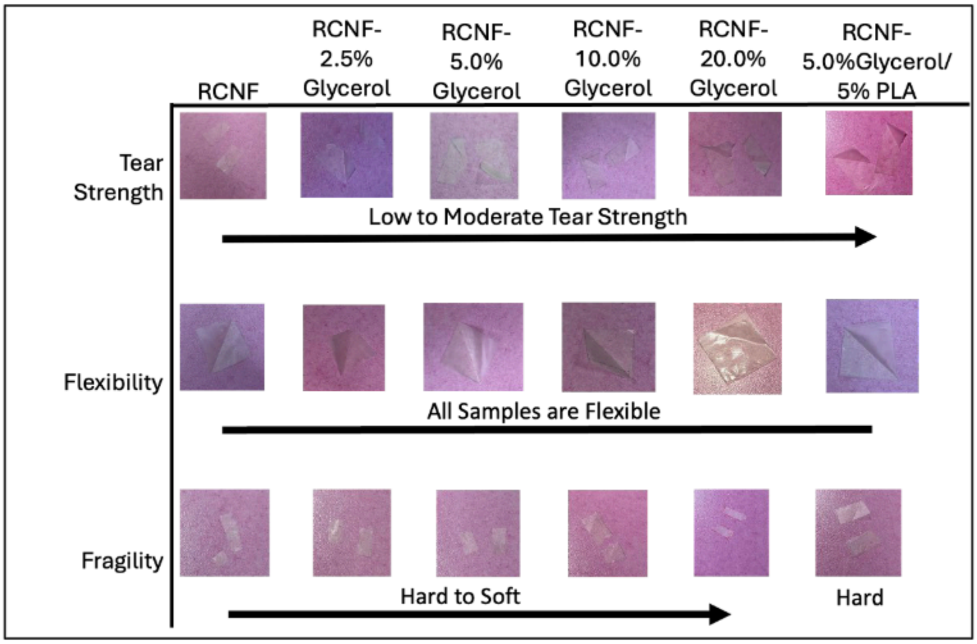

Fig. 4. Mechanical behaviour of RCNF interacted with different glycerol concentrations and PLA

Meanwhile, the tearing ability and the effects on the films showed that higher concentrations of glycerol and the addition of PLA resulted in a better tearing effect, where the films without glycerol were the easiest to tear smoothly, exhibiting the lowest tear strength. The lamination with recycled PLA further enhanced film integrity, as evidenced by smoother tearing behaviour and improved resistance to deformation, suggesting effective stress distribution through polymer–cellulose chain entanglement [16, 19, 22]. Hence, increasing glycerol concentration significantly enhances the ductility of the films. The reference sample of RCNF films exhibited brittle behaviour due to strong intermolecular hydrogen bonding between cellulose chains, while glycerol incorporation significantly improved ductility by plasticising the cellulose network and increasing chain mobility where in common practice, plasticisers such as glycerol are used to improve elasticity and ductility properties of other films including cellulose and other biopolymer-based films. In the case of CNF, the molecules of glycerol reduce the friction between CNF fibrils, thereby decreasing fibril-fibril interactions [13, 26]. Consequently, introducing glycerol into the cellulose-based polymer matrix affects the properties of the material by competing with hydrogen bonding between polymer chains and the plasticiser. This competition reduces direct interactions among polymer chains, resulting in increased flexibility and elongation of the material [23, 30].

Therefore, increasing the plasticiser concentration enhances hydrogen bonding, thereby reducing cohesion between cellulose molecules by promoting hydrogen bond formation between the hydroxyl groups of cellulose and glycerol. This contributes to the increased flexibility and elongation of the bioplastic [31]. Quantitative mechanical tests, such as tensile strength and elongation at break, were not performed due to challenges in maintaining uniform sample size and thickness inherent to the solvent-assisted lamination process, as noted in previous studies on PLA recycling and film formation [17, 21]. Moreover, this study primarily focused on understanding the physicochemical interactions and the relationship between water uptake and biodegradation as the key factors in the early stages of material development [20, 32]. Nevertheless, the qualitative mechanical assessment provides a meaningful preliminary evaluation of handling performance, and future work will incorporate standardized mechanical testing to quantitatively correlate composition, mechanical strength, and degradation characteristics.

3.4 Water Absorption and Swelling Kinetic Study

The water absorption behaviour of the RCNF, RCNF/glycerol, and RCNF/glycerol/recycled PLA laminated films was investigated to evaluate the influence of plasticisation and lamination on moisture sensitivity. Fig. 5 shows that all samples exhibited a rapid initial increase in water uptake followed by a gradual approach to equilibrium, indicating a diffusion-controlled absorption process commonly observed in cellulose-based composites. The pure RCNF film showed the highest water absorption due to the abundance of hydrophilic hydroxyl groups capable of forming hydrogen bonds with water molecules [13]. The incorporation of glycerol further increased water uptake, as glycerol enhances chain mobility and introduces additional hydrophilic sites that facilitate water diffusion into the cellulose network [33].

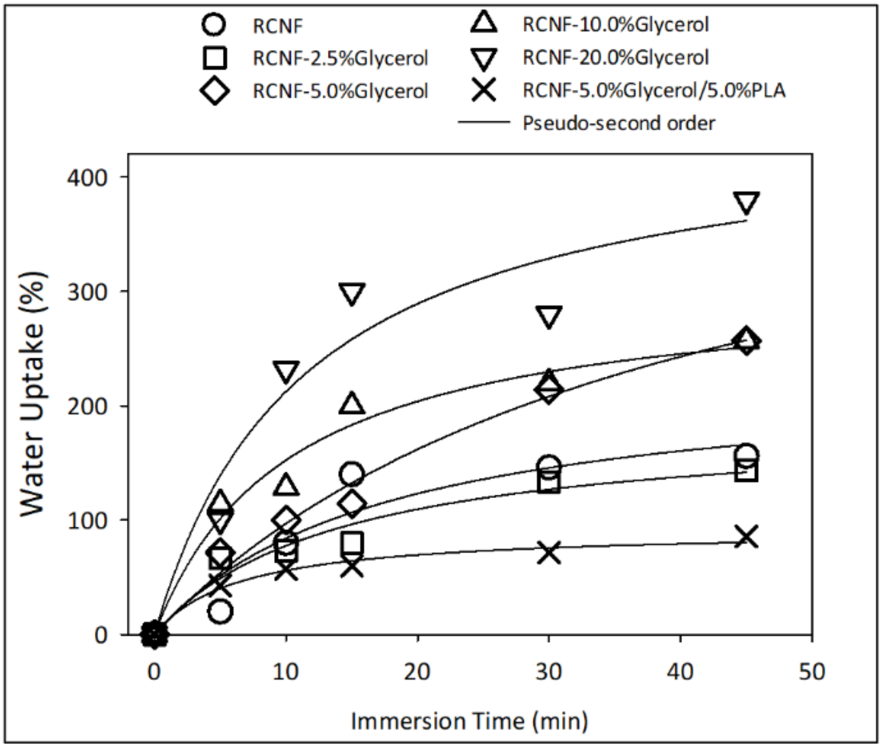

Fig. 5. Adsorption kinetics of water uptake fitted to the pseudo-second order for RCNF, RCNF/Glycerol and RCNF/Glycerol/PLA films

In contrast, the RCNF/glycerol/recycled PLA laminated films exhibited significantly reduced water absorption compared to glycerol-plasticised RCNF films. This reduction is attributed to the hydrophobic nature of PLA, which acts as a barrier layer that limits direct contact between water molecules and the

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hydrophilic cellulose matrix. The laminated PLA layer reduces available diffusion pathways and restricts moisture transport by decreasing free volume at the cellulose and PLA interface. Additionally, PLA chain entanglement and interfacial adhesion with the regenerated cellulose layer contribute to the formation of a denser interfacial structure, further hindering water penetration into the composite film [34 - 35].

Although swelling behaviour was discussed in relation to water uptake, quantitative thickness swelling or dimensional change measurements were not conducted in this study due to limitations in film thickness uniformity associated with the solvent-assisted lamination process. Therefore, swelling is inferred from water absorption trends rather than direct dimensional analysis. During the water uptake study, the pores on the surface of the films absorbed water even within the first 5 min. The films continued to absorb water up to 45 min until the equilibrium phase was reached, at which point the pores were no longer available to absorb additional water molecules. Hence, the addition of PLA restricted the absorption of water molecules by the porosity of the film due to chain entanglement. Moreover, the pseudo-second-order kinetic model provided a strong fit for the water uptake behaviour of bioplastics, with the swelling kinetics of the RCNF film showing greater consistency with this model and yielding a higher correlation coefficient. They were governed primarily by interfacial diffusion resistance imposed by the hydrophobic PLA layer rather than direct chemical affinity and the water uptake process [25, 30]. These results indicate that while glycerol promotes water uptake and swelling through enhanced hydrophilicity, the incorporation of recycled PLA effectively moderates moisture sensitivity by restricting water diffusion pathways within the composite structure

3.5 Biodegradation via Soil Burial of RCNF/PLA Films in Soil

A biodegradability test was established to regulate the degradation rate of films through a weight loss test in soil at different incubation temperatures. The physical appearance of the films is shown in Fig. 6 and Fig. 7 where it is evident that the films had been degraded after 10 days of incubation. The degraded films became fragmented at 25 °C and burst at 50 °C soil burial temperature which also correlated to the weight loss test results, as shown in Fig. 6. The graph indicates that the higher the incubation temperature led to greater weight loss for all films, consistent with previous studies showing that elevated temperature can enhance hydrophilic diffusion and microbial enzymatic activity in soil environments, accelerating biodegradation rates [36]. This effect may be attributed to increased polymer chain mobility, enhanced moisture diffusion, and more active soil microbial communities at higher temperatures, which together promote faster breakdown of polymer matrices. This is associated to the hydrophilic nature of cellulose, which easily absorbs moisture due to the existence of hydroxyl groups in cellulose [23, 31, 36]. In addition, soil microorganisms are able to attack the cellulose films, leading to deterioration of the cellulose structure [32, 34]. Furthermore, in comparison to glycerol content, higher glycerol loading reduces the biodegradation rate of cellulose films, possibly due to the physical structure of the composite and the effect of barrier, which hinders penetration of water into the film [35-36]. Although the glycerol increases water uptake due to its hydrophilicity, it also plasticises the cellulose network, stabilising the matrix and potentially reducing accessible sites for microbial degradation under the conditions tested [37].

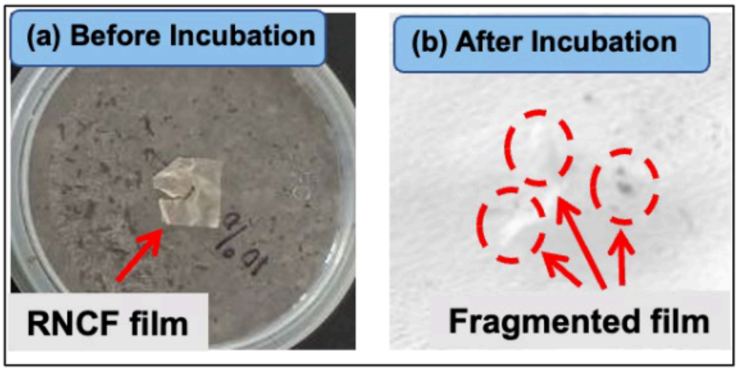

Fig. 6. Physical appearance of cellulose/glycerol/PLA (a) before incubation, (b) after incubation

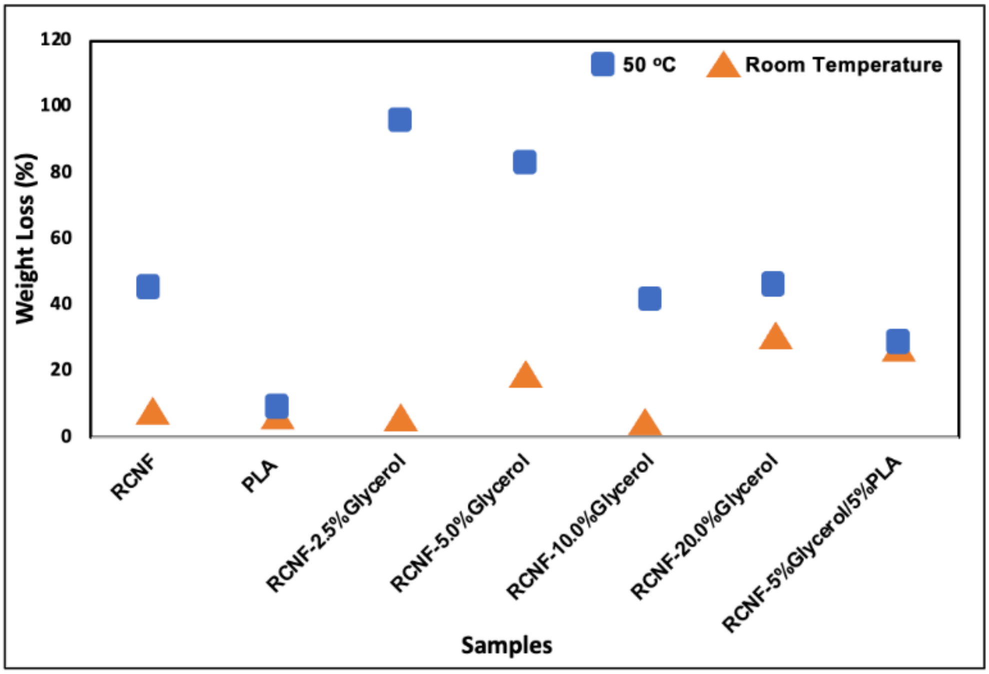

Fig. 7. Weight loss test of RCNF, PLA, RCNF with different glycerol content and RCNF/Glycerol/PLA films after burial at room temperature and 50 °C

4. CONCLUSIONS

Regenerated cellulose nanofibre, encapsulated with glycerol at varying concentrations and laminated with PLA, offers a promising solution for repurposing the abundant PLA waste, particularly from the 3D printing industry. These films exhibit enhanced properties, as the addition of glycerol acts as a plasticiser, improving flexibility by enabling water uptake of up to 300% of their original weight at 20% glycerol content. Mechanical property analysis reveals that glycerol improves tear strength and foldability, while the inclusion of PLA enhances the durability of the films, creating a balanced set of characteristics.

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Consequently, these films, with their flexibility and durability, are well-suited for use as packaging materials. This process provides an eco-friendly alternative for manufacturing industries, enabling the production of biodegradable plastics for specific applications and contributing to the reduction of plastic pollution.

5. ACKNOWLEDGMENTS/FUNDING

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6. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

7. AUTHORS' CONTRIBUTIONS

Hatika Kaco: Conceptualisation, writing-original draft, supervision, funding acquisition; Noorul Jannah Aizul Hussin: Methodology and formal analysis; Syahidatul Nadhilah Shah Lail: Methodology and formal analysis; Mohd Shaiful Sajab: Writing- review and editing; Nuradlyna Safyah Mohd Rozi; Methodology and formal analysis; Muhammad Naqib Hamdan: writing- review and editing; Amir Mustaqim Mohd Naim: Formal analysis and editing; Muizzuddin Muhammad Nazri: Methodology and formal analysis.

8. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the author(s) used Grammarly and ChatGPT in order to check language, grammar and used to assist in drafting sections of the introduction and to improve the clarity of the language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

9. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

Available upon request: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request

10. ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Sains Islam Malaysia.

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