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Development of Nutmeg Shell (*Myristica Fragrans)* Powder-Reinforced Starch Bioplastic Films

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***Abstract*— The increasing accumulation of agricultural residues has encouraged their valorization as biofillers in biodegradable polymer systems. This study developed starch-based bioplastic films incorporating *Myristica fragrans* (nutmeg) shell powder and quantified the effect of filler concentration on tensile strength, water absorption, thickness, and soil-burial weight loss. Films were prepared by solution casting using corn starch and agar as matrix materials, glycerol as a plasticizer, and nutmeg shell powder at 0, 3.23, 6.25, 9.09, and 11.76% (w/w). For corn starch-based films, mean tensile strength decreased from 15.58 N at 0% to 8.82 N at 3.23% filler and subsequently increased to 13.89 N at 11.76%. Water absorption (Mean) increased progressively from 24.98% to 66.65%, while film thickness increased from 1.26 mm to 1.98 mm at 9.09% filler and remained at 1.94 mm at 11.76%. Seven-day soil-burial weight loss increased from 6.57% in the unfilled film to 33.17% at 11.76% filler. In contrast, agar-based films exhibited a progressive reduction in tensile strength (mean) from 31.23 N at 0% to 7.93 N at 11.76% filler, while water absorption ranged from 60.83% to 72.20%. At 6.25% nutmeg shell powder, the corn starch film exhibited a tensile strength of 9.70 N, water absorption of 35.55%, thickness of 1.96 mm, and seven-day soil-burial weight loss of 20.40%, with coefficients of variation of 0.03, 0.11, 0.12, and 0.10, respectively. These results establish the concentration-dependent effects of *M. fragrans* shell powder on starch-based bioplastic film properties and demonstrate its feasibility as a lignocellulosic biofiller for biodegradable film development.**

Keywords: *Myristica fragrans*; nutmeg shell powder; bioplastic film; corn starch; biofiller; biodegradation.

I. INTRODUCTION

The environmental persistence of petroleum-derived plastics has increased interest in biodegradable materials produced from renewable resources, particularly for short-life applications such as packaging. Among the available biopolymers, starch has attracted considerable attention because it is renewable, biodegradable, widely available, and readily processed into films. Recent studies have demonstrated the potential of starch obtained from agricultural resources for sustainable film development (Goncalves et al., 2024). However, starch-based films remain limited by their sensitivity to moisture and relatively weak mechanical performance, making material modification necessary for applications requiring greater structural stability (Oluwasina et al., 2021).

At the same time, agricultural processing generates substantial lignocellulosic residues that can potentially be incorporated into biodegradable polymers rather than discarded. The use of such residues as biofillers offers a practical link between bioplastic development and agricultural-waste valorization, supporting a more circular approach to material use (Shanmugam et al., 2021). In particular, nutshell wastes have attracted recent attention because their lignocellulosic structure allows them to be incorporated into biodegradable composite systems (McNeill et al., 2024).
Nevertheless, the contribution of a natural filler cannot be assumed to be beneficial at all concentrations; changes in filler loading can influence particle distribution, matrix–filler interactions, moisture response, and ultimately the physical and mechanical behaviour of the resulting material (Kalla, 2021; McNeill et al., 2024). Nutmeg shell is an agricultural waste generated in large quantities during nutmeg processing. It is primarily composed of lignocellulosic

components such as cellulose, hemicellulose, and lignin, making it a valuable bio resource for reinforcing bioplastics. Nutmeg shell is one such agricultural residue with potential for further material utilization (Figure 1). It contains approximately 28.63% cellulose, 9.51% hemicellulose, and 50.14% lignin (Idris et al., 2018), indicating a substantial lignocellulosic fraction suitable for investigation as a particulate biofiller. Despite this composition, the use of nutmeg shell powder in biodegradable film systems remains comparatively underexplored, particularly with respect to how filler concentration affects mechanical behaviour, moisture uptake, film thickness, and degradation (Goncalves et al., 2024). Addressing this gap, the present study developed corn starch- and agarbased bioplastic films containing 0, 3.23, 6.25, 9.09, and 11.76% nutmeg shell powder. The resulting films were evaluated for tensile behaviour, water absorption, thickness, and seven-day soil-burial weight loss to determine how increasing filler concentration influences film performance and to assess the feasibility of valorizing nutmeg shell waste as a biofiller in biodegradable film.



Figure 1 Nutmeg (Myristica fragrans) shell

II. Materials and Methods

A. Preparation of nutmeg shell powder and bioplastic films

Myristica fragrans (nutmeg) shells were cleaned, dried, mechanically ground, and sieved to obtain a fine powder for use as the lignocellulosic filler. Corn starch and agar were used as the film-forming matrices, glycerol as the plasticizer, and distilled water as the dispersion medium. The films were prepared by solution casting, which is commonly employed for starch-based film formation (Goncalves et al., 2024). Five formulations containing 0, 3.23, 6.25, 9.09, and 11.76% (w/w) nutmeg shell powder were prepared for each matrix. Each formulation contained 10 g of corn starch or agar, 60 mL of distilled water, and 5 mL of glycerol, while the nutmeg shell powder content was varied from 0 to 10 g (Table 1). The constituents were mixed thoroughly and heated at 70 °C for approximately 3 min under continuous stirring, following the processing conditions adapted from Kasmuri et al. (2018). The resulting film-forming mixtures were cast onto trays and dried under ambient conditions before characterization.

Table 1 Composition of the developed bioplastic films

Formulation	Matrix (g)	Nutmeg shell powder (%)	Nutmeg shell powder (g)	Water (mL)	Glycerol (mL)
A1	10	0	0	60	5
A2	10	3.23	2.5	60	5
A3	10	6.25	5.0	60	5
A4	10	9.09	7.5	60	5
A5	10	11.76	10.0	60	5
B1	10	0	0	60	5
B2	10	3.23	2.5	60	5
B3	10	6.25	5.0	60	5
B4	10	9.09	7.5	60	5
B5	10	11.76	10.0	60	5

A1–A5: corn starch-based films; B1–B5: agar-based films.

B. Film Characterization

The developed bioplastic films were characterized for maximum tensile load, water absorption, thickness, and soil-burial weight **loss** to evaluate the influence of nutmeg shell powder concentration on film performance. Fifteen replicate specimens (n = 15) from each formulation were evaluated for each property**,** and the results were expressed as mean values with their corresponding variability.

Tensile behaviour was evaluated using a universal tensile testing machine following the ASTM D882based procedure adopted in this study. The maximum load sustained by each specimen was recorded in N**.** Water absorption was determined using the ASTM D570-98-based procedure (Simorangkir et al., 2026). Specimens were initially weighed, immersed in distilled water at 27 °C for 30 min, and reweighed after immersion. The percentage increase in mass was used to determine water absorption.

Film thickness was measured using a Vernier caliper. Measurements were taken at five different locations on each 2 × 2 cm specimen, and the mean thickness was calculated. Short-term degradation behaviour was assessed using 4 × 4 cm specimens subjected to a seven-day soil-burial test, with percentage mass loss determined from the difference between the initial and final dry masses (Ubaidah et al., 2024).

Experimental data were analysed using descriptive statistics, including the mean, minimum, maximum, standard deviation (SD), and coefficient of variation (CV). These parameters were used to compare the measured responses across the different nutmeg shell powder concentrations and to assess the variability among replicate specimens.

III. . RESULTS AND DISCUSSION

Potato starch films developed fungal growth during drying and conditioning and were excluded from subsequent characterization. The discussion therefore focuses on corn starch- and agar-based films containing 0–11.76% nutmeg shell powder. The mean values of the measured properties are summarized in Tables 2 and 3.

Table 2 Mean properties of nutmeg shell powdercorn starch reinforced bioplastic films

Nutmeg shell powder (%)	Tensile response (N) Corn starch	Water absorption (%) Corn starch	Thickness (mm) Corn starch	Weight loss (%) Corn starch
0	15.58	24.98	1.26	6.57
3.23	8.82	27.78	1.45	16.57
6.25	9.70	35.55	1.96	20.40
9.09	10.88	40.28	1.98	32.60
11.76	13.89	66.65	1.94	33.17

Table 3 Mean properties of nutmeg shell powderagar-reinforced bioplastic films

Nutmeg shell powder (%)	Tensile response (N) Agar	Water absorption (%) Agar	Thickness (mm) Agar	Weight loss (%) Agar
0	31.23	60.83	0.50	16.60
3.23	27.38	71.40	0.70	16.60
6.25	19.84	72.20	0.96	16.60
9.09	10.16	61.70	1.10	33.33
11.76	7.93	66.25	1.36	33.33

A. Mechanical and physical properties

Nutmeg shell powder produced distinctly different tensile responses in the two matrices. In corn starch films, the mean maximum tensile load decreased from 15.58 N for the unfilled control (A1) to 8.82 N at 3.23% filler (A2), and then progressively recovered to 9.70, 10.88, and 13.89 N at 6.25, 9.09, and 11.76%, respectively. Although the value at 11.76% remained below that of the control, the recovery at higher filler levels indicates that the mechanical response was not linear. Agar films behaved differently: the mean maximum tensile load declined continuously from 31.23 N for B1 to 27.38, 19.84, 10.16, and 7.93 N as the filler concentration increased. Thus, nutmeg shell powder did not act as a universally reinforcing filler; its contribution depended on the matrix and loading level. Comparable concentration-dependent behaviour has been reported for lignocellulosic particle-filled systems, where particle dispersion, interfacial adhesion, and stress transfer influence the measured mechanical response (Kalla, 2021; McNeill et al., 2024; Zaaba et al., 2013). Because interfacial morphology was not examined in the present study, the contrasting responses of corn starch and agar should be interpreted as experimental trends rather than evidence of a specific reinforcement mechanism.

Water absorption also depended on both filler loading and matrix type. In corn starch films, the mean value increased progressively from 24.98% for A1 to 27.78, 35.55, 40.28, and 66.65% for A2-A5, respectively. The pronounced increase at 11.76% indicates that high filler loading reduced resistance to moisture uptake. Agar films were more water-sensitive across the tested range, recording 60.83-72.20% absorption, although the response was not monotonic. This behaviour is consistent with the hydrophilic character of starch and lignocellulosic fillers. Nutmeg shell contains approximately 28.63% cellulose and 9.51% hemicellulose, in addition to 50.14% lignin (Idris et al., 2018); hydroxyl-containing polysaccharide fractions can interact readily with water. Similar increases in moisture uptake following incorporation of natural fillers have been reported for starch-based biocomposites (Kalla, 2021; Oluwasina et al., 2021). The results therefore identify moisture sensitivity as an important limitation when selecting filler loading for potential short-life film applications. The contrast between the two matrices was also evident at intermediate filler levels: at 6.25% filler, corn starch films absorbed 35.55% water compared

with 72.20% for agar films, whereas at 9.09% the corresponding values were 40.28 and 61.70%. At the highest loading, the values converged to 66.65% for corn starch and 66.25% for agar. This pattern reinforces moisture sensitivity as a key limitation of the unmodified fillermatrix systems, consistent with recent starch-bioplastic studies that identify water resistance as an important requirement for packaging performance (Gurunathan et al., 2025; Jafarzadeh et al., 2026).

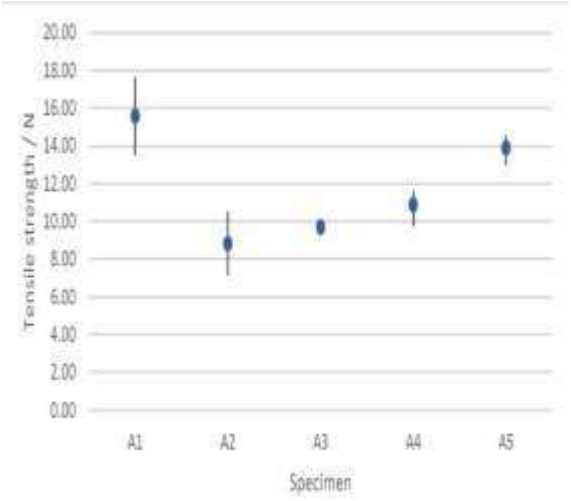


Figure 2 Maximum tensile load of corn starchbased films at different nutmeg shell powder concentrations

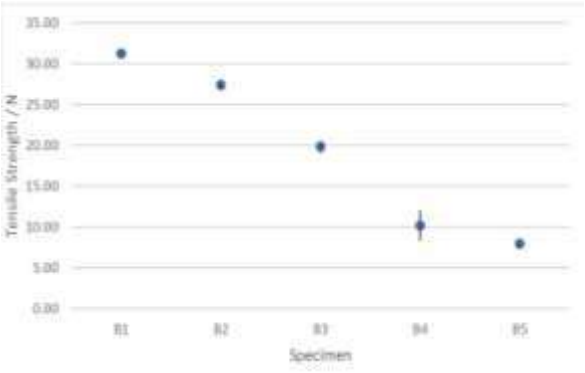


Figure 3 Maximum tensile load of agar-based films at different nutmeg shell powder concentrations

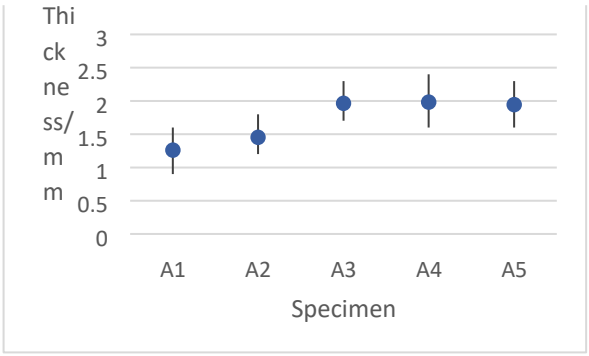


Figure 4 Effect of nutmeg shell powder concentration on the thickness of corn starchbased bioplastic films

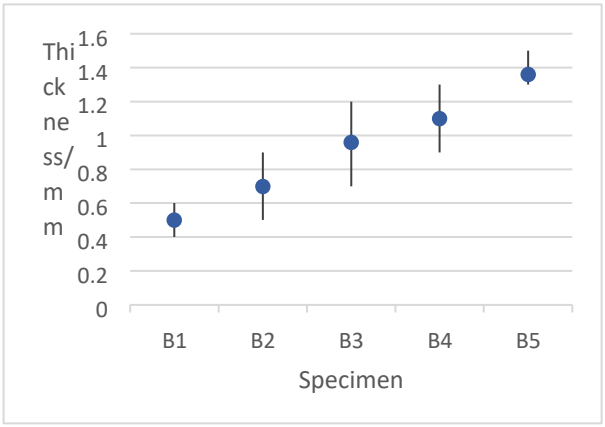


Figure 5 Effect of nutmeg shell powder concentration on the thickness of agar-based bioplastic films

Film thickness increased with nutmeg shell powder loading in both matrices. For corn starch films, mean thickness increased from 1.26 mm in A1 to 1.45 mm in A2 and reached 1.96-1.98 mm in A3 and A4, before decreasing slightly to 1.94 mm in A5. A3 showed comparatively consistent thickness measurements (SD = 0.24 mm), whereas A4 showed greater variation (SD = 0.36 mm). Agar films displayed a more regular increase, from 0.50 mm in B1 to 0.70, 0.96, 1.10, and 1.36 mm in B2-B5, respectively. The overall increase is consistent with the greater solid fraction introduced into the casting mixture as filler content increased (Kasmuri et al., 2018). However, the small decrease observed for A5 indicates that thickness was not governed by filler quantity alone. Variations in particle distribution or casting uniformity may have contributed, but morphological analysis would be required to confirm this interpretation.

B. Soil-burial weight loss and overall response

Nutmeg shell incorporation was associated with greater short-term soil-burial mass loss, particularly in the corn starch matrix. After seven days, mean mass loss increased from 6.57% for A1 to 16.57, 20.40, 32.60, and 33.17% for A2-A5, respectively. Agar films showed a different pattern: B1-B3 each

recorded 16.60% mean mass loss, followed by an increase to 33.33% for both B4 and B5. The higher mass loss observed at the two greatest filler concentrations suggests that increasing the lignocellulosic fraction altered the susceptibility of the films to the soil-burial environment. This trend is consistent with the biodegradable character of starch and plant-derived lignocellulosic constituents reported in biocomposite systems (Naveena et al., 2020; Shanmugam et al., 2021). Nevertheless, the present test quantified mass loss after only seven days and should not be interpreted as evidence of complete biodegradation or mineralization. Longer-duration testing under controlled conditions is required to establish the degradation kinetics of the developed films. Considering all measured responses, higher nutmeg shell loading increased soil-burial mass loss but was also accompanied by greater moisture uptake, while mechanical behaviour remained strongly matrixdependent. Among the reinforced corn starch formulations, A3 (6.25%) provided an intermediate combination of 9.70 N maximum tensile load, 35.55% water absorption, 1.96 mm thickness, and 20.40% seven-day mass loss, with a low tensile CV of 0.03. This formulation should therefore be regarded as a comparatively consistent intermediate composition rather than a statistically proven optimum. From a material-design perspective, the combined results show that the response to nutmeg shell addition cannot be judged from a single property. The corn starch system retained a greater proportion of its control load-bearing response at the highest filler level than the agar system, but this was accompanied by a substantial rise in water absorption. Conversely, the agar control exhibited the highest initial maximum tensile load, yet its mechanical response deteriorated steadily as shell content increased. This contrast highlights the importance of matrix selection when lignocellulosic residues are introduced into biodegradable films. Recent studies on starch-based packaging materials similarly emphasize that mechanical integrity, water sensitivity, and biodegradation must be considered together because modification of one response may adversely affect another (Gurunathan et al., 2025; Jafarzadeh et al., 2026). The present results therefore support concentration-specific formulation rather than assuming that the maximum possible biofiller loading will provide the most useful film. The variability data provide an additional basis for interpreting formulation consistency. For example, the tensile response of A3 showed a CV of 0.03, while its water absorption, thickness, and seven-day mass-loss responses showed CV values of 0.11, 0.12, and 0.10, respectively. These values indicate relatively controlled variation within the tested specimens, although descriptive statistics alone cannot establish statistically significant differences among formulations. Accordingly, terms such as 'significant improvement' or 'optimum formulation' are avoided here unless supported by inferential testing. Future studies should apply appropriate analysis of variance and post-hoc comparisons to determine whether differences among filler levels are statistically distinguishable. In addition, particle-size characterization and microscopic examination would help determine whether the observed changes arise from particle dispersion, agglomeration, interfacial adhesion, or changes in film continuity.

The visual appearance of the developed films at different nutmeg shell powder concentrations is presented in Figure 6. Increasing filler loading produced visible changes in the films, alongside the measured changes in thickness and other physical properties.



Fig. 6. Visual appearance of films: A1–A5, corn starch; B1–B5

Recent work on fibre-reinforced bioplastics also demonstrates the value of combining mechanical and biodegradation measurements when assessing waste-derived reinforcement systems (Simorangkir et al., 2026). Such characterization would provide a stronger mechanistic basis for selecting nutmeg shell loading for a defined end use.

IV. Conclusion

Nutmeg shell powder was successfully incorporated into corn starch- and agar-based bioplastic films, and the results demonstrate that film performance was governed by both filler concentration and matrix type. Increasing filler content generally increased film thickness, moisture uptake, and seven-day soil-burial mass loss. The mechanical response was matrixdependent: corn starch films showed an initial reduction followed by partial recovery in maximum tensile load, whereas agar films exhibited a continuous decline as filler loading increased.

Among the reinforced corn starch formulations, A3 containing 6.25% nutmeg shell powder showed a comparatively consistent intermediate response, with a maximum tensile load of 9.70 N, water absorption of 35.55%, thickness of 1.96 mm, and seven-day

soilburial mass loss of 20.40%. These findings support the feasibility of valorizing nutmeg shell as a lignocellulosic biofiller, while also showing that increasing filler concentration does not improve all film properties simultaneously.The main limitations of the study are the absence of direct filler-matrix interfacial characterization and the short duration of the soil-burial assessment. Future work should therefore examine particle size and dispersion, interfacial morphology, moisture-barrier performance, longerterm biodegradation, and application-specific mechanical behaviour before the developed films are considered for packaging or other short-life applications.

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