RESEARCH PAPER

"Development Of Cellulose-Based Biodegradable Packaging Material From Musa Acuminata Leaves"

***Dr. Vanitha G Ramesh[1*] & Chiranth Jain [2]**

[1*]Professor, Department of Life Sciences, Indian Academy Degree College Autonomous, Bengaluru,
dr.vanitha.lifesciences@indianacademy.ac.in
[2]M.Sc. Scholar, Indian Academy Degree College Autonomous, Bengaluru.

Abstract:
The increasing environmental impact of conventional petroleum-based plastics has heightened demand for sustainable, biodegradable packaging alternatives. This study investigates the use of leaves from the common agricultural by-product *Musa acuminata* to produce eco-friendly packaging materials. Cellulose was extracted through chemical treatments, including bleaching and alkaline processing, to remove lignin and hemicellulose; the purified cellulose was then formed into biodegradable films using suitable plasticizers. Key physicochemical properties—tensile strength, elongation at break, water absorption, and biodegradability—were evaluated, revealing excellent mechanical strength, flexibility, and degradation performance that make these films ideal for packaging applications. By valorizing banana leaf waste, this approach reduces environmental pollution and supports the circular economy. Overall, the study demonstrates that cellulose derived from *Musa acuminata* leaves offers a viable, environmentally friendly alternative to traditional plastic packaging, advancing sustainable material development and environmental conservation.

Keywords: Musa acuminata leaf cellulose, Biodegradable packaging, Alkali extraction, Mechanical properties, Sustainable materials, Waste valorisation

How to cite this article: Ramesh VG, Jain C. Development Of Cellulose-Based Biodegradable Packaging Material From Musa Acuminata Leaves. Int J Drug Deliv Technol. 2026;16(32s):1160-1167. DOI: 10.25258/ijddt.16.32s.129.

Introduction:

Humanity must urgently reconsider how plastics are produced and used to prevent them from becoming waste, as over 8 million tons of plastic enter the oceans each year, a figure expected to double over the next 20 years. Large quantities of plastic packaging leak into the environment, with only 14% recovered for recycling, costing the global economy between $80 and $120 billion annually; if current trends continue, ocean plastic may outweigh fish by 2050 (Yaradoddi et al., 2020a). Globally, approximately 400 million tons of plastic waste are generated each year, primarily from packaging within urban waste streams (Lampitt et al., 2023; Bergmann et al., 2022), yet only about 10% is recycled, 14% incinerated, and the remaining 76% disposed of in landfills or the environment (Tennakoon et al., 2023). Plastic pollution poses severe ecological risks, as larger debris can entangle or be ingested by marine fish, birds, and mammals, while micro- and nanoplastics are readily consumed by organisms such as mussels and zooplankton, allowing accumulation within food chains (Gerritse et al., 2020). In developing countries, inadequate waste management often leads to plastic burning, releasing toxic gases that threaten human health and exacerbate environmental degradation, while plastic consumption also contributes to petroleum resource depletion (Tennakoon et al., 2023). These environmental, economic, and health impacts have intensified the need to replace conventional non-biodegradable plastics with biodegradable alternatives (Sunita Ranote et al., 2024). As a result, researchers are increasingly developing bioplastics derived from renewable resources, such as hydrolyzed keratin and starch, due to their sustainability and degradability (Bergel & Santana et al., 2020; Tiruwork Zewudie Admasie et al., 2024). Although

starch-based bioplastics show great promise because of their abundance and biodegradability, their weak mechanical strength and poor water stability limit widespread application (Yang et al., 2023). Nevertheless, starch-based films are widely explored for food packaging due to their favorable properties and ease of processing, alongside other polysaccharides such as alginate, pectin, and chitosan, which provide excellent gas barrier performance, transparency, flexibility, stability, and resistance to oil and fats (Jayachandra S. Yaradoddi et al., 2020). Carboxymethyl cellulose (CMC) is a biodegradable, non-toxic cellulose derivative widely used in biopolymer films for sustainable packaging applications. It is produced from agricultural waste cellulose through alkalization with NaOH followed by etherification using sodium monochloroacetate, with reaction conditions affecting yield and degree of substitution. Due to its excellent film-forming ability, water-binding capacity, and mechanical strength, CMC is a promising alternative to conventional plastic packaging materials (Shiva Hadimani et al., 2023). Biodegradable polymeric films are produced using methods such as solution casting, extrusion, and thermo-compression, primarily from starch- and cellulose-based polymers. The incorporation of biopolymers like CMC and natural plasticizers such as glycerol or sorbitol significantly enhances mechanical, thermal, and barrier properties. These films

*Author for Correspondence: dr.vanitha.lifesciences@indianacademy.ac.in

exhibit good biodegradability and functional performance, making them promising materials for sustainable food packaging applications (Cabernard et al., 2022).

Banana plants (Musa acuminata), native to Southeast Asia, thrive in tropical climates (20-30°C, pH 5.5-7.0) and are major crops in India, Philippines, and Brazil. Rapid growth (9-12 months) from suckers yields fruit bunches; needs water, nutrients, pest control (e.g., Panama disease). Supports economies via trade and sustainability through intercropping. 35-45% cellulose (β-1,4-glucan microfibrils), 10-20% hemicelluloses, 5-10% lignin for strength. Includes polyphenols, saponins, alkaloids. Ideal for eco-fibers, textiles, biocomposites (Varma et al., 2019).

Polymeric Film Formation.Starch-based bioplastic films are developed via casting, blown extrusion, or thermo-compression, often blending CMC from sugarcane bagasse with gelatin (1.5%), agar (2%), and glycerol (2-2.5%) plasticizers for optimal properties (Versino et al., 2016; Yaradoddi et al., 2020). Films characterized by FTIR, DSC, TGA assess structure, thermal stability, swelling, solubility, permeability (water vapor/O2), and biodegradability (soil burial). Yam starch films (4% starch, 1.3% glycerol, 0.11 mm thick) maximize puncture strength; glycerol increases permeability and deformation (Mali et al., 2004; Yaradoddi et al., 2020). Active starch films with antimicrobials (e.g., potassium sorbate) extend produce shelf life (strawberries, Brussels sprouts); composites enhance mechanics for packaging (Versino et al., 2016). Cellulose-based materials generally have lower tensile strength than traditional plastics like HDPE or metals like steel. They offer greater elasticity and flexibility, with a lower modulus allowing more deformation under stress before breaking (Karimah et al., 2021).

Native and modified starches enable fully biodegradable, edible, low-cost films (Versino F et al., 2016). Biopolymers offer a cost-effective replacement for petroleum-based plastics, with competitive mechanical properties (Melissa Gurgel Adeodato Vieira et al., 2011). Food wastes (e.g., cassava/banana/pineapple peels, durian/jackfruit/avocado seeds, chicken feathers, sludge) rich in starch, cellulose, and other biopolymers provide eco-friendly packaging alternatives. This approach reduces both plastic and food waste, enhancing sustainability (M O Ramadhan et al., 2020).

The primary goal was to develop cost-effective, biodegradable packaging from agriculture waste-derived carboxymethyl cellulose (CMC). This reduces reliance on expensive commercial CMC, transforming waste into sustainable films suitable for packaging (Jayachandra S. Yaradoddi et al., 2020). Microbial activity tests assessed bioplastic breakdown in composting soil. Banana leaf bioplastics significantly boosted microbial activity, with higher microbe concentrations around samples versus controls. This indicates bioplastics promote microbial growth and degradation Pathma, J., & Sakthivel, N. (2012).

Applications and Performance as a packaging material, Banana leaf bioplastics showed adequate flexibility and biodegradability for food wrappers and bags, ideal for single-use applications minimizing environmental impact. It acts as an agriculture films /mulching films, they provided effective soil coverage and weed control, biodegrading into harmless residues to reduce field waste.

It also acts as a disposable Cutlery, the material offered good strength and flexibility but needs improved moisture resistance and durability; formulation optimization continues.

Materials and methods:

1. Plant Material

Musa acuminata leaves, collected from agricultural fields in Kolar, Karnataka, India (13.094627ºN, 78.124834ºE), were dried, powdered, and stored at room temperature for low-cost bioplastic production.

2. Extraction of the crude cellulose pulp from Musa Acuminata

48.44 g of Musa acuminata leaves were oven-dried at 80°C overnight, blended, and sieved (0.5 mm mesh). Cellulose pulp was extracted, with moisture content calculated as pre/post-drying weight difference percentage (Huang et al., 2017a).

3. Bleaching and Extraction of Cellulose Pulp

5 g dried Musa acuminata material was bleached in 80 mL 0.5% acetic acid + 1% sodium chlorite at 95°C for 2 hr (Chia et al., 2015). Pulp was filtered, washed with tap water (process repeated 3x for delignification), rinsed with 50 mL deionized water, oven-dried at 80°C overnight, and weighed.

Calculation for cellulose yield

$$\text{Cellulose yield (\%)} = A/B \times 100$$

were,

A= the weight of the pulp (g).

B= the weight of the dried plant material (g).

4. Production of carboxymethyl cellulose

CMC was prepared from Musa plant leaves by mixing 80 mL isopropyl alcohol with 10 mL of 20% NaOH and shaking thoroughly (Thenapakiam et al., 2013). The mixture was added to 5 g of cellulose pulp and incubated in a water bath at 40, 50, or 60 °C for 1 h to alkalize the cellulose. Etherification was then carried out by adding 3 g sodium monochloroacetate and maintaining the reaction at 60 °C for 3 h (Huang et al., 2017b).

The solid residue was filtered through muslin cloth, suspended in 100 mL methanol, and neutralized to pH 7 with 10% acetic acid to remove residual NaOH (Rachtanapun et al., 2012). After overnight storage, the formed CMC was filtered, washed with aqueous methanol, and oven-dried at 80 °C for 3 h. The dried CMC was powdered, and yield from 5 g of cellulose pulp was recorded in grams.

Confirmatory test for CMC

4.1. Foam test

A 0.1% sample solution was vigorously shaken; the absence of foam confirmed sodium carboxymethyl cellulose, distinguishing it from other cellulose ethers, alginates, and natural gums (Sodium Carboxymethyl Cellulose, n.d.).

4.2. Precipitate formation

Equal volumes of 0.5% sample solution and 5% copper sulfate or aluminum sulfate were mixed; precipitate formation confirmed sodium carboxymethyl cellulose, distinguishing it from other cellulose ethers, gelatin, carob bean gum, and tragacanth gum (Sodium Carboxymethyl Cellulose, n.d.).

4.3. Preparation of Polymeric Blends

CMC was extracted from Musa plant leaves and blended with gelatin, agar, and 2.5% glycerol to prepare films. A mixture of 1.2 g CMC, 1.15 g gelatin, and 0.55 g agar was dissolved in distilled water to 100 mL, stirred at 50 °C for 2 h to obtain a uniform solution. The viscous solution was cast onto Petri dishes or glass plates and oven-dried for 24–36 h, after which the polymeric films were carefully removed.

4.4. Determination of Thickness of the film

A screw gauge (micrometer) is a precision instrument used to measure very small dimensions, such as the thickness of sheets or diameter of thin wires. It consists of a U-shaped frame with a threaded spindle and thimble, where the screw pitch represents the axial distance moved per rotation, enabling measurements more precise than those obtained with a Vernier caliper (Chauhan et al., n.d.).

Formula for calculation;

Total reading = Main scale reading + (Circular scale reading × Least count of the gauge)

5. Environmental compatibility test

5.1 Biodegradation test

Two 500 mL glass bottles were filled with agricultural soil and vermicompost. Film samples (≈4 × 2.5 cm), weighed and cut into small pieces, were buried at a depth of 5 cm. To enhance microbial activity, 20 mL water was added. Samples were retrieved after 3, 5, and 7 days, reweighed, and percentage weight loss was calculated.

5.2 Swelling test

To assess the sustainability and retention of the bioplastic, swelling tests were performed in centrifugation tubes. Pieces of each sample were pre-weighed. Swelling studies were conducted in three separate solvent systems: water, chloroform, and methanol. The pre-weighed film samples were immersed in the solvent media for approximately 2 hours. The weight gain of the tested samples was then calculated relative to their initial weights and recorded (Ijaz et al., n.d.).

5.3 Solubility test

All samples were cut into small pieces and placed into test tubes containing various solvents to assess solubility. Solubility was evaluated as fully soluble, partially soluble, or insoluble. The solvents used included ammonia, acetic acid, chloroform, acetone, methanol, sulfuric acid, orthophosphoric acid, ethanol, and water (Yaradoddi et al., 2020c).

5.4 Determination of oil permeability coefficient and water permeability (WP)

For the oil permeability test, 5 mL of edible oil was added to a test tube, which was then sealed with a film sample. The sealed tube was inverted and placed centrally on pre-weighed filter paper, positioned along the sidewall, and left for 24 hours. After incubation, the filter paper was reweighed using an electronic balance, and the oil permeability coefficient was calculated using the provided equation.

$$P0=(\Delta W\times FT)/(S\times T)$$

P_0 is the oil permeability coefficient (g·mm/(m^2·day),

ΔW difference in the filter paperweight (g);

FT is the thickness of the film (mm),

S is the area of the film (m^2),

T is incubation time (in days)

Results and Discussions:

Material and Efficiency

Yield: The production of bioplastics from Musa acuminata leaves involves several key stages including collection, cleaning, drying, milling, and chemical processing.

The results indicate that the overall yield of cellulose obtained from dried banana leaves ranges between 20–30% of the initial biomass. The reduction in mass is primarily due to the removal of non-cellulosic components such as lignin and hemicellulose during the purification process.

Efficiency: In terms of process efficiency, the extraction method proved to be highly effective, enabling the recovery of approximately 85–90% of the available cellulose. This high extraction efficiency demonstrates the suitability of banana leaves as a reliable and sustainable raw material for bioplastic production.

Figure 1: Bleaching and extraction of cellulose

6.1 Quality of Extracted Cellulose

The cellulose obtained from banana leaves demonstrates encouraging properties.

Purity: The purity of the extracted cellulose ranges between 70–80%, depending on the effectiveness of the processing and purification methods employed.

Fiber Characteristics: In terms of fiber characteristics, the extracted fibers have lengths ranging from 0.5 to 1.5 mm, making them suitable for use as reinforcement in bioplastic matrices. Their favorable aspect ratio contributes significantly to improving the mechanical strength of the resulting material.

6.2 Confirmatory tests for CMC

To confirm that the extracted product was CMC, conducted the foam test and precipitation test.

A) Foam test:

Figure 2: Foam test

The samples were tested negative for the foam test, as no foam was produced.

B) Precipitate formation

Figure 3. Precipitate formation

We concluded that the samples tested positive for the precipitation test, as a precipitate was produced.

6.4. Preparation of Polymeric Blends

The addition of carboxymethyl cellulose (CMC) to gelatin solutions increases the availability of reactive sites along the polypeptide chains, thereby enhancing hydrogen bonding and electrostatic interactions. Elevated CMC concentrations further intensify these interactions by promoting cationic–anionic associations between polymer chains. This results in

strengthened intra- and intermolecular networks, facilitating the formation of stable films with enhanced flexibility (Yaradoddi et al., 2020d).

Figure 8: Polymeric film developed

6.5 Thickness of the film

Total Reading = Main Scale Reading + (Thimble Reading × Least Count)

Least Count is the smallest division on the screw gauge and is usually determined by the formula:

Least Count = Pitch of the Screw / Number of Divisions on the Thimble

- Pitch of the Screw: This is the distance the spindle moves per complete rotation of the thimble. It's often given in the gauge's specifications.
- Number of Divisions on the Thimble: Typically, this is 50 or 100, but it should be specified in the gauge's manual.

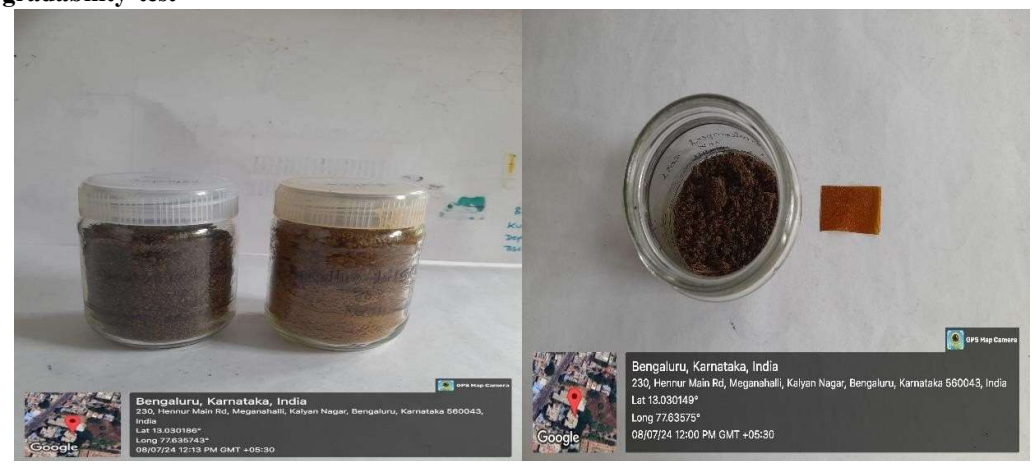
Least count [L.C = 0.01]

SL NO	MSC (A)	CSR(N)	B= N*LC	D+A=B
1	0.5	58	0.58	1.08
2	0.5	58	0.58	1.08
3	0.5	60	0.60	1.1

Mean = 1.08+1.08+1.1/3 = 1.086mm

6.6 Environmental Susceptibility tests

6.6.1 Biodegradability test



Research indicates that CMC degradation aligns with the breakdown of carbonyl groups and highly interactive side chains. The crystalline structure of CMC enhances thermal stability when blended with gelatin-agar solutions. Consequently, CMC-gelatin films exhibit higher thermal decomposition temperatures compared to pure gelatin films.

Subjecting the bioplastic for Biodegradability test Mechanical and Biodegradable Properties

The developed bioplastic films were subjected to biodegradability testing to evaluate their environmental performance. Effective packaging materials must exhibit sufficient mechanical strength to safeguard contents while also being fully biodegradable to ensure safe decomposition without causing environmental pollution.
The results indicate that the prepared films possess both high tensile strength and excellent biodegradability, demonstrating their suitability as sustainable packaging materials (Arıkan & Bilgen, 2019).

Thickness of the film
Total Reading = Main Scale Reading + (Thimble Reading × Least Count)

Least Count is the smallest division on the screw gauge and is usually determined by the formula:
Least Count = Pitch of the Screw / Number of Divisions on the Thimble

- Pitch of the Screw: This is the distance the spindle moves per complete rotation of the thimble. It's often given in the gauge's specifications.
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Least count [L.C = 0.01]

Mean 1.086mm =

SL NO	MSC (A)	CSR(N)	B= N*LC	D+A=B
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3	0.5	60	0.60	1.1

1.08+1.08+1.1/3 =

Soil Sample	Sample	Initial weight (g) (zero days)	Grams weight loss after 3 days of incubation and % of degradation	Grams weight loss after 5 days of incubation and % of degradation	Grams weight loss after 7 days of incubation and % of degradation
No. of Days		0	3	5	
Agricultural soil	A	0.34g	0.07g(20.58%)	0.0g(100%)	-
	B	0.30g	0.11g(36.53%)	0.01(9%)	0g(100%)
	C	0.37g	0.15g(40%)	0.05g(33%)	0g(100%)
Vermicompost soil	A	0.30g	0.19g(63.33%)	0g(100%)	-
	B	0.27g	0.17g(56.65%)	0.09g(52.94%)	0g(100%)
	C	0.31g	0.21g(67.74%)	0.14g(66%)	0g(100%)

Conclusion:
This study demonstrates the successful utilization of ce llulose from Musa acuminata leaves to produce biodegr adable packaging.The resulting films' acceptable mech anical, flexible, and biodegradable properties demonstr ated promise as an eco-
friendly replacement for conventional plastics.
Utilizing banana leaves also promotes waste valorizati on and the creation of sustainable materials.
However, improvements in both the profitability of lar gescale production and moisture resistance are needed.
All things considered, this study shows that cellulose d erived from Musa acuminata has potential as a sustainable packaging material.

Acknowledgement:
I sincerely express my gratitude to Indian Academy Degree College (Autonomous) for providing the laboratory facilities necessary to carry out this research work. I also extend my thanks to the students who assisted me in transforming this idea into meaningful research findings.

REFERENCES:
1. Yaradoddi, J. S., Banapurmath, N. R., Ganachari, S. V., Soudagar, M. E. M., Mubarak, N. M., Hallad, S., Hugar, S., & Fayaz, H. (2020). Biodegradable carboxymethyl cellulose based material for sustainable packaging application. *Scientific Reports, 10*(1), 21960. https://doi.org/10.1038/s41598-020-78912-z
2. Gerritse, J., Leslie, H. A., de Tender, C. A., Devriese, L. I., & Vethaak, A. D. (2020). Fragmentation of plastic objects in a laboratory seawater microcosm. *Scientific Reports, 10*(1), 7051. https://doi.org/10.1038/s41598-020-67927-1
3. Lampitt, R. S., Fletcher, S., Cole, M., et al. (2023). Stakeholder alliances are essential to reduce the scourge of plastic pollution. *Nature Communications, 14*,

2849. https://doi.org/10.1038/s41467-023-38613-3

4. Walther, B. A., & Bergmann, M. (2022). Plastic pollution of four understudied marine ecosystems: A review of mangroves, seagrass meadows, the Arctic Ocean and the deep seafloor. *Environmental Reviews, 30*(4), 565–592. https://doi.org/10.1139/er-2022-0029.
5. Cabernard, L., Pfister, S., Oberschelp, C., & Hellweg, S. (2022). Growing environmental footprint of plastics driven by coal combustion. *Nature Sustainability, 5*(11), 957–964. https://doi.org/10.1038/s41893-021-00807-2.
6. Tennakoon, P., Pathum Chandika, Myunggi, & Won-Kyo Jung. (2023). Marine-derived biopolymers as potential bioplastics, an eco-friendly alternative. *International Journal of Biological Macromolecules, 26*(4), 106404.
7. Ranote, S., Kowalczuk, M., Guzenko, N., et al. (2024). Towards scalable and degradable bioplastic films from Moringa oleifera gum. International Journal of Biological Macromolecules, 269(Pt 2), 132219. https://doi.org/10.1016/j.ijbiomac.2024.132219.
8. Ranote, S., Kowalczuk, M., Guzenko, N., et al. (2024). Towards scalable and degradable bioplastic films from Moringa oleifera gum. International Journal of Biological Macromolecules, 269(Pt 2), 132219. https://doi.org/10.1016/j.ijbiomac.2024.132219
9. Admasie, T. Z., et al. (2024). Alkaline keratinase from Bacillus sp. DRS4 efficiently biodegrades chicken feathers to synthesize improved keratin/bacterial nanocellulose-based bioplastics. Heliyon, 10(12), e33250.
10. Oluwasina, O. O., Olaleye, F. K., Olusegun, S. J., Oluwasina, O. O., & Mohallem, N. D. S. (2024). Influence of oxidized starch on physicomechanical, thermal properties, and atomic force micrographs of cassava starch bioplastic film. International Journal of Biological Macromolecules, 135, 282–293
11. Admasie, T. Z., et al. (2024). Alkaline keratinase from Bacillus sp. DRS4 efficiently biodegrades chicken feathers to synthesize improved keratin/bacterial nanocellulose-based bioplastics. Heliyon, 10(12), e33250.
12. Oluwasina, O. O., Olaleye, F. K., Olusegun, S. J., Oluwasina, O. O., & Mohallem, N. D. S. (2024). Influence of oxidized starch on physicomechanical, thermal properties, and atomic force micrographs of cassava starch bioplastic film. International Journal of Biological Macromolecules, 135, 282–293
13. Mali, S., Grossmann, M. V. E., García, M. A., Martino, M. N., & Zaritzky, N. E. (2004). Barrier, mechanical and optical properties of plasticized yam starch films. Food Hydrocolloids, 19(1), 157–164. https://doi.org/10.1016/j.foodhyd.2004.04.008.
14. Versino, F., López, O. V., García, M. A., & Zaritzky, N. E. (2016). Starch based films obtained by casting, blown extrusion and thermo-compression moulding processes for antimicrobial packaging of fruits and vegetables. *Food Hydrocolloids, 61*, 821–833. https://doi.org/10.1016/j.foodhyd.2016.06.017
15. Yaradoddi, J. S., Banapurmath, N. R., Ganachari, S. V., Soudagar, M. E. M., Mubarak, N. M., Hallad, S., Hugar, S., & Fayaz, H. (2020). Biodegradable carboxymethyl cellulose based material for sustainable packaging application. *Scientific Reports, 10*(1), 21960. https://doi.org/10.1038/s41598-020-78912-z
16. Karimah, A., Ridho, M. R., Munawar, S. S., Ismadi, Amin, Y., Damayanti, R., Lubis, M. A. R., Wulandari, A. P., Nurindah, Iswanto, A. H., Fudholi, A., Asrofi, M., Saedah, E., Sari, N. H., Pratama, B. R., Fatriasari, W., Nawawi, D. S., Rangappa, S. M., & Siengchin, S. (2021). A comprehensive review on natural fibers: Technological and socio-economical aspects. In Polymers (Vol. 13, Issue 24). MDPI. https://doi.org/10.3390/polym13244280.
17. **Chia, Y. C., Lim, H. M., & Ching, S. M. (2015).** *Use of chronic kidney disease to enhance prediction of cardiovascular risk in those at medium risk.* **PLoS ONE**, *10*(10), e0141344. https://doi.org/10.1371/journal.pone.0141344.
18. Yang Y, Gatica D, Liu X, Wu R, Kang R, Tang D, Klionsky DJ (2023).Similar importance of inter-tree and intra-tree variations in wood density observations in Central Europe. 1. PII: S2950-1555(24)00010-7. DOI: https://doi.org/10.1016/j.greenca.2024.01.004.
19. Jayachandra S. Yaradoddi, J.S., Banapurmath, N.R., Ganachari, S.V., Soudagar, M.E., Mubarak, N.M., Shankar, H., Shoba, H. and Fayaz, H., 2020. Biodegradable carboxymethyl cellulose based material for sustainable packaging application. Scientific Reports, 10(1), 2160. https://doi.org/10.1038/s41598-020-59165-2.
20. Varma, V., & Bebber, D. P. (2019). Climate change impacts on banana yields around the world. In *Nature Climate Change* (Vol. 9, Issue 10, pp. 752–757). Nature Publishing Group. https://doi.org/10.1038/s41558-019-0559-9
21. Cabernard, L., Pfister, S., Oberschelp, C., & Hellweg, S. (2022). "Growing environmental footprint of plastics driven by coal combustion." Volume 9 – 2022. https://doi.org/10.3389/fmars.2022.981439.
22. Noorjahan, C.M., Banu, S.N., & Subhashree, V. (2022). Bioplastic synthesis using banana peels and its characterization. *Journal of Pharmaceutical Negative Results*, 13(S7), 2855-2863. https://doi.org/10.47750/pnr.2022.13.S07.380.
23. Yaradoddi, J.S., et al. (2021). Biodegradable carboxymethyl cellulose based material for

sustainable packaging application. *Scientific Reports*, 10, 22687. **https://doi.org/10.1038/s41598-020-78912-z**

24. Arıkan & Bilgen (2019) refers to a study on bioplastic production from potato peel waste, focusing on biodegradability. The full reference is: Arıkan, E.B., & Bilgen, H.D. (2019). Production of bioplastic from potato peel waste and investigation of its biodegradability. *International Advanced Researches and Engineering Journal*, 3(2), 75-83.