

# Sustainable Bio-Polymer films infused with plant leaf extracts

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## ABSTRACT

*The day-to-day utilization of plastic products in agricultural operations has exhibited a consistent increase. Plastic materials are utilized at multiple agricultural stages, ranging from sowing processes to post-harvest product packaging. Among these applications, plastics are extensively used in mulch films and packaging. To make these applications sustainable and eco-friendly, synthesis of biodegradable films by integrating v/v% aqueous extracts of Neem, Eucalyptus, and Moringa leaves is attempted in this study. These plants extracts are used into a polyvinyl alcohol-glycerin-starch matrix. As these plants leaves extracts contains of bioactive compounds such as flavonoids, tannins, alkaloids, glycosides and terpenoids. Films were cast via solvent casting and air-dried. FTIR analysis further supported the incorporation of these phytochemicals, as evidenced by characteristic O-H, C=C, C-O, N-H, and C-H stretching bands, which were absent in the standard film without any plant extract. Degradation kinetics of grapes wrapped inside the films showed an increase in shelf life under both room and refrigerated conditions. These results suggest that bio-films instilled with plant extracts offer a sustainable and functional alternative to conventional packaging, combining enhanced food preservation with environmental compatibility. Besides this such films can be used as a replacement to conventional mulch films as the soil burial studies showed enhanced biodegradability in all films, with Eucalyptus-based films degrading the fastest.*

**Keyword:** Bio-film, Plant Extracts, Synthesis, Biodegradation, Packaging

## 1. INTRODUCTION

Bioplastics are defined by international standards as plastics derived from renewable biomass, capable of biodegradation, or both. Standards such as ASTM D6400 and ISO 17088 outline the specific conditions under which a plastic must biodegrade to be classified as compostable. For example, ASTM D6400-19 requires that a plastic must disintegrate to less than 10% of its original weight within 84 days and mineralize at least 90% of its organic carbon to CO<sub>2</sub> within 180 days. Bioplastics are categorized into bio-based and biodegradable (e.g., PLA, PHAs, TPS), biodegradable but petrochemical-based (e.g., PBAT, PCL), and bio-based but non-biodegradable (e.g., bioPET, bioPE). Packaging remains the largest application segment, though their use is expanding into agriculture, textiles, and automotive sectors.[1]

The demand for biodegradable films is increasing rapidly due to their environmental advantages over traditional plastics. In agriculture, films are used for mulching and greenhouse applications, contributing significantly to plastic use. However, petroleum-based plastics used in these applications pose major environmental challenges due to their non-degradable nature. Biodegradable plastics offer a promising solution by decomposing naturally and reducing plastic accumulation in ecosystems. In India, the adoption of biodegradable films in agriculture can improve soil health, reduce pollution, and increase yield while aligning with sustainable development goals. This shift is essential for minimizing environmental impact and promoting responsible resource use.

## 2. LITERATURE REVIEW

Fredi et.al. (2023) reviewed compatibilization strategies for biopolymer blends, highlighting reactive chemistries and nanoparticle incorporation to improve PLA toughness while maintaining biodegradability [1]. Ashothaman et.al. (2021) evaluated reinforcement methods for PLA composites to enhance thermal stability, impact resistance, and applicability in biomedical and automotive sectors [2]. Elfaleh et.al. (2023) examined natural-fiber-polymer composites, emphasizing surface treatments to improve compatibility and reduce moisture sensitivity in automotive

and aerospace applications [3]. Lamberti et.al. (2020) analyzed global plastic pollution and proposed mechanical, chemical recycling, and bioplastic adoption (PLA, PHA, bio-PET) as sustainable waste-management strategies [4]. Muthukumar et.al. (2014) compared mechanical properties of sisal, jute, and kenaf hybrid composites with glass fiber, concluding jute/glass composites offered superior tensile and impact performance [5]. Siracusa et.al. (2020) surveyed advances in bio-PE, bio-PP, and bio-PET, detailing processing technologies, applications, and environmental benefits of green plastics [6]. Zhu et.al. (2016) explored renewable monomer feedstocks (CO<sub>2</sub>, terpenes, oils) and catalysis approaches for sustainable polymer and composite production [7]. Hottle et.al. (2013) conducted life-cycle assessments of PLA, PHA, and TPS versus petroleum-based plastics, finding comparable environmental impacts when end-of-life scenarios were included [8].

Mirpoor et.al. (2022) utilized Naviglio® technology to extract phenol-rich Cardoon leaf extracts, integrating them into gelatin hydrogels to enhance swelling capacity and impart antibacterial properties [9]. Poonkodi et.al. (2022) formulated bio-nanocomposite films with carboxymethylcellulose, chitosan, nanoclays, and lemon leaf extract, demonstrating extended freshness in jasmine flower packaging [10]. Ghoshal et.al. (2020) fabricated starch–CNF nanocomposite films with varying CNF content and Eucalyptus globulus extract, achieving superior barrier, antioxidant, and antimicrobial performance for grape preservation [11]. Kotb et.al. (2023) introduced agarose–chitosan dendritic colloid composites, exhibiting four-fold toughness improvement, high transparency, and bactericidal activity with confirmed soil biodegradability [12]. Manotham et.al. (2023) developed PVA/Centella asiatica electrospun nanofibers, revealing concentration-dependent morphology, mechanical properties, and notable antibacterial efficacy [13]. Chen et.al. (2023) engineered ultra-strong PVA–cellulose nanofiber composites with dynamic hydrogen bonds, achieving exceptional mechanical and healing properties alongside biodegradability [14]. Ko et.al. (2024) isolated fungal strains that degraded PBAT–PLA–TPS bio-plastic films, achieving near-complete degradation when used in a consortium with TPA-degrading bacteria [15]. Parangusan et.al. (2024) combined neem gum with PVA to produce dielectric composites with enhanced conductivity and high dielectric constants, targeting flexible energy storage applications [16]. Shweta et.al. (2023) investigated banana peel–reinforced biodegradable plastics, demonstrating enhanced tear resistance and nutrient-releasing degradation in soil [17]. Vikas et.al. (2023) assessed starch/PVOH mulch films reinforced with flax and hemp fibers, achieving high tensile strength and ~85% field degradation compared to 10% for synthetic films [18]. Taweechaisupapong et.al. (2014) evaluated *Streblus asper* leaf extract for subgingival biofilm inhibition, achieving over 70% anti-biofilm activity against key periodontal pathogens [19]. Chodankar et.al. (2024) examined *Mangifera indica* and *Anacardium occidentale* extracts for maxillofacial silicone disinfection, showing significant CFU reductions comparable to 0.2% chlorhexidine [20].

### 3. MATERIAL AND METHODS

#### 3.1 Raw materials

Neem, Eucalyptus, and Moringa leaves were procured from the Institute of Chemical Technology, Mumbai campus.

#### 3.2 Chemicals

Polyvinyl alcohol, Starch, Glycerine were of analytical grade and purchased from Molychem, SRL Chem and Kabson industries respectively.

#### 3.3 Aqueous extraction of plant leaves

##### 3.3.1 Pre-processing, drying and pulverization of plant leaves

Neem, eucalyptus, and moringa leaves were initially washed to remove surface impurities. The leaves were then placed in separate trays, and their fresh weights were recorded. Subsequently, they were subjected to controlled drying in a hot air oven under specific conditions. Neem leaves were dried at 65°C for 36 hours, eucalyptus leaves at 65°C for 48 hours, and moringa leaves at 50°C for 8 hours. Post-drying, the leaves were reweighed to determine weight loss and then pulverized using a commercial mixer. The weight of the resulting powdered material was measured to calculate the powder yield for each batch. The powdered samples then underwent a biphasic extraction process to obtain aqueous extracts, which were subsequently utilized for the synthesis of biofilms.

##### 3.3.2 Powder Yield

Yield of powder was calculated after each batch pulverization. Yield of powder was calculated using:

$$\text{Powder yield\%} = \frac{\text{Weight of pulverised powder}}{\text{Weight of fresh leaves}} \times 100$$

### 3.3.3 Bi-phasic separation method

This process involved adding the pulverized powder to one liter of distilled water, heating the mixture to 100 °C while stirring continuously for one hour. The resulting solution was then filtered using a funnel fitted with Whatman filter paper (10 cm diameter, 11 µm pore size) placed over a flask or measuring cylinder, allowing filtration to proceed for 24 hours. After filtration, the extract was transferred into bottles and stored under refrigeration to prevent degradation or oxidation at room temperature. At each production stage, volume measurements were recorded to quantitatively calculate extract yields.

### 3.3.4 Extract Yield

Yield of extract was calculated after collection of extract in bottles. Yield of extract was calculated using:

$$\text{Extract yield\%} = \frac{\text{Volume of extract obtained}}{\text{Volume of solvent used}} \times 100$$

### 3.4 Preparation of films

The principle method of preparing starch–PVA films was based on solution-casting. Initially, 5.6 g of PVA was dissolved in 40 mL of distilled water at 150°C while stirring at 1000 rpm for 20 minutes. After this process, 60 mL of water was added to dilute the solution, followed by 5.6 g of starch and 4.8 mL of glycerine. Various concentrations (5, 10, 15, 20, 25% v/v) of plant extracts: Neem, Moringa, or Eucalyptus were then added to the solution. The entire mixture was stirred until uniform. Once solution was properly mixed, the solution was cast into glass petri plates. These mixtures were left to dry in natural sunlight for four days. Once dried, the films were peeled off and stored in airtight pouches under refrigerated conditions to prevent degradation. The weight and thickness of each film were taken for further analysis.



Fig- 1: Prepared films of varying concentrations of plant extracts.

### 3.5 Preliminary phytochemical screening

Phytochemical screening was conducted to identify bio-active compounds in the plant extracts using standard qualitative assays:

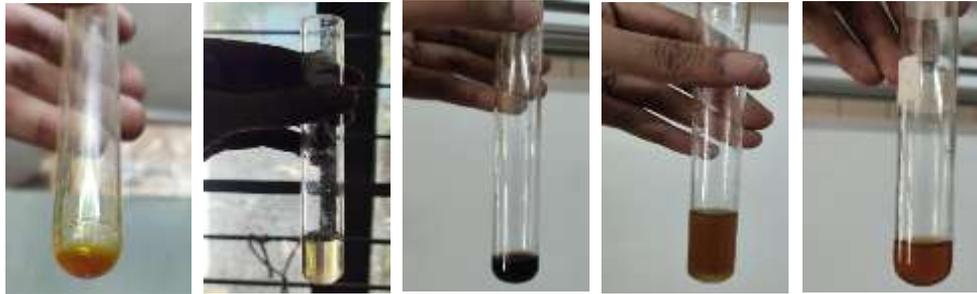
**a. Alkaloids Test:** The test for detecting alkaloids involved adding 1 mL of Dragendorff's reagent to 2 mL of the extract solution. The reaction was monitored, and the formation of an orange-brown precipitate was noted as the endpoint, confirming the presence of alkaloids.

**b. Flavonoids Test:** The test involves adding two to three drops of sodium hydroxide to 2 mL of the extract. Initially, a deep yellow color appeared, but it gradually became colorless upon adding a few drops of dilute HCl, indicating the presence of flavonoids.

**c. Tannins Test:** In this test, two millilitres (2 mL) of the aqueous solution of the extract were added to a few drops of 10% ferric chloride solution (light yellow). The occurrence of a blackish-blue color indicated the presence of Gallic tannins, while a green-blackish color suggested catechol tannins.

**d. Steroids/Terpenoids Test:** In this test, 1 mL of the aqueous solution of the extract was dissolved in 2 mL of chloroform, and a few drops of sulfuric acid were added carefully. The formation of a reddish-brown color ring at the interface confirmed the presence of steroids.

**e. Glycosides Test:** In this test, solution of 0.5 mL, containing glacial acetic acid and 2-3 drops of ferric chloride, was mixed with 5 mL of the extract. Later, 1 mL of concentrated H<sub>2</sub>SO<sub>4</sub> was added along the walls of the test tube. The appearance of a reddish-brown color at the junction of the two liquids indicated the presence of cardiac glycosides.



**Fig-2:** Phytochemical tests as per incremental order.

### 3.6 Packaging Test

This test was conducted to assess the shelf-life of grapes using four film types: a control film and three films containing 25% plant extracts. Each film was divided into two sections, with four grapes sealed in each section. The first half samples were stored at  $25 \pm 1^\circ\text{C}$  (room temperature) while other half were kept at  $5 \pm 1^\circ\text{C}$  (refrigeration) conditions which could be seen in Fig-3. Daily weight measurements were done to calculate degradation rate, with the test concluding when visible rot occurred. The film that maintained grape freshness longest under each storage condition was identified as most effective.



**Fig-3:** Films kept in room temperature and refrigerator.

### 3.7 Soil Degradation Test

This test was conducted to assess the biodegradability of films by monitoring their weight loss over time in agricultural soil conditions. Four types of films were tested: a standard batch and three films containing 25% extracts of neem, eucalyptus, and moringa. As shown in Fig-4, each film was cut into uniform pieces, initially weighed, and buried in agricultural soil to ensure consistent exposure. The films were retrieved monthly for weight measurements using a digital analytical balance. Soil particles were gently removed before reweighing, and the percentage weight loss was calculated to determine the extent of degradation over period of six months.



**Fig-4:** Films buried under soil for degradation test.

### 3.8 Fourier transform infrared spectroscopy (FTIR)

FTIR was done in the wavelength range of 500–4000 cm<sup>-1</sup> at room temperature by using Berker Alpha FTIR (USA) spectrophotometer using 20 mg of film samples.

## 4. RESULTS AND DISCUSSIONS

### 4.1 Preprocessing, drying and pulverization of plant leaves.

Neem, Eucalyptus, and Moringa leaves underwent three sequential processes: pre-processing, drying, and pulverization. As shown in Fig-5(a), two batches of each species were collected, and their fresh weights were recorded. These samples were then dried in a hot-air oven under species-specific conditions as seen in Fig-5 (b). After drying, the leaves were pulverized, and the resulting powders were sealed in airtight pouches as seen in Fig-5 (c). Weights were measured both before preprocessing and after pulverization to determine the powder-yield%.



Fig-5: (a) Pre-processing, (b) Drying in hot air oven (c) Pulverized powder.

### 4.2 Powder yield

Yield of powder obtained of each species were recorded after post-processing of each batch. Weight of fresh leaves before heating and powders after being pulverized were taken until constant weight was obtained. Table 1 shows the weight of each batch before and after the entire process, and yield of powder. Chart-1 shows that the first batch of neem had the highest powder yield percentage, while the second batch of neem had the lowest yield percentage out of all the batches.

Table -1: Weight of batches before\after the process.

BATCH NO	WT OF FRESH LEAVES	WT OF POWDER	YIELD%
N-01	30 g	12 g	40%
N-02	124 g	30 g	24.19%
E-01	96 g	34 g	35.41%
E-02	136 g	50 g	36.76%
MO-01	94 g	24 g	25.53%
MO-02	94 g	24 g	25.53%

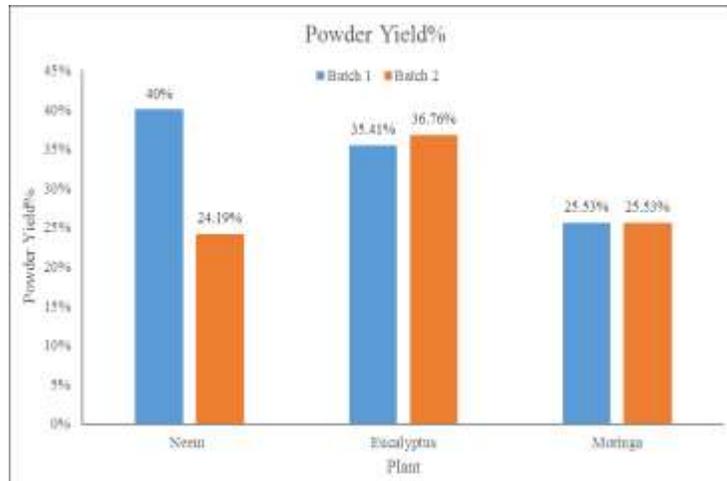


Chart -1: Comparative analysis of powder yield obtained across batches.

### 4.3 Bi-phasic separation

The separation process was carried out by mixing the pulverized leaf powder with one liter of distilled water, followed by continuous stirring at 100 °C for one hour. The resulting mixture was filtered through Whatman filter paper (10 cm diameter, 11 μm pore size) using a funnel positioned over a flask or measuring cylinder as can be seen in Fig-6. Filtration was allowed to proceed undisturbed for 24 hours to ensure maximum recovery. Post-filtration, the obtained extracts were collected in labeled bottles and stored under refrigeration to minimize oxidative or thermal degradation. At completion of filtering, the volume of the each recovered extract was measured, enabling calculation of the extract yield percentage. Variations in extract yield across different plant types were observed, indicating differences in solubility, and extraction efficiency based on species and leaf composition.



Fig-6: Extracts were prepared by heating, settling, and filtering powdered plant material.

### 4.4 Extract yield

Extract yield for each batch was calculated following proper filtration. Table 2 presents the volume of solvent used, the volume of extract obtained, and the corresponding extract yield (%) for each batch. Chart-2 shows that the first batch of moringa had the highest extract yield percentage, while the second batch of neem had the lowest yield percentage out of all the batches.

Table -2: Extract Volume and Yield Percentage across batches

BATCH NO	VOLUME OF OBTAINED EXTRACT	VOLUME OF DISTILLED WATER	YIELD%
N-01	472 ml	1000 ml	47.2%

N-02	602 ml	1000 ml	60.2%
E-01	750 ml	1000 ml	75%
E-02	779 ml	1000 ml	77.9%
MO-01	865 ml	1000 ml	86.5%
MO-02	823 ml	1000 ml	82.3%

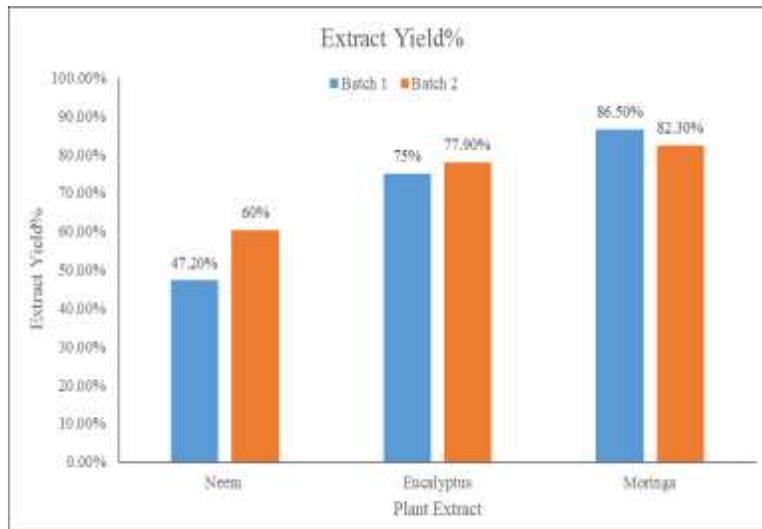


Chart -2: Comparative analysis of extract yield obtained across batches.

#### 4.5 Preparation of films

Three different plant extracts (Neem, Eucalyptus, and Moringa) were used to analyse their impact on the weight and thickness of biofilms. As you can see in Table-3, the results indicate that Neem extract at 5% concentration yielded the highest weight, while the standard batch (0% extract) showed the lowest weight. In terms of thickness, the thinnest biofilms were observed for Eucalyptus extract at 5% and Moringa Oleifera at both 5% and 20% concentrations, whereas the standard batch, sample without extract exhibited the greatest thickness. These findings highlight the influence of both extract type and concentration on the biofilm’s physical properties, with significant variations observed in weight and thickness across different samples.

Table -3: Weight and thickness measurements of films at various extract concentrations

Film	Concentration%	Weight	Thickness
Standard Batch	0	14.82	1.5
Neem	5	18.61	1.3
Neem	10	18.12	1.5
Neem	15	14.91	1.3
Neem	20	15.06	1.3
Neem	25	14.69	1.2
Eucalyptus	5	17.74	1
Eucalyptus	10	15.22	1.3
Eucalyptus	15	14.78	1.3
Eucalyptus	20	15.17	1.2

Eucalyptus	25	15.65	1.5
Moringa	5	14.03	1
Moringa	10	16.32	1.3
Moringa	15	16.16	1.5
Moringa	20	15.32	1
Moringa	25	14.59	1

#### 4.5 Preliminary phytochemical screening

The phytochemical analysis of Neem, Eucalyptus, and Moringa reveals the presence of key bioactive compounds that contribute to their preservative properties. As seen in Table-4, these plants share common constituents like flavonoids, alkaloids, tannins, and terpenoids, which demonstrate significant antioxidant, antimicrobial, and therapeutic effects. While cardiac glycosides are found in Neem and Moringa, enhancing their protective action against pathogenic damage, they are notably absent in Eucalyptus. These compositional differences imply that each plant may possess unique biological activities and varying degrees of efficacy in different applications.

Table -4: Phytochemicals tests done on the extracts.

Phytochemicals	Tests	Neem	Eucalyptus	Moringa
Alkaloids	Dragendoff's reagent	✓	✓	✓
Flavonoids	Alkaline reagent	✓	✓	✓
Tannins	Ferric Chloride	✓	✓	✓
Terpenoids	Salkowski test	✓	✓	✓
Glycosides	Keller-Killani test	✓	✗	✓

#### 4.6 PACKAGING TEST

The packaging performance evaluation using grapes as a test commodity revealed significant temperature-dependent variations in film degradation, as illustrated in Chart-3 (a) and Chart-3 (b). At ambient conditions ( $25 \pm 1^\circ\text{C}$ ) over a period of 15 days, grapes in eucalyptus, 25% film showed the lowest degradation rate, because of their high terpenoid content, while the grapes in moringa, 25% degraded the most among the extract films. However, grapes in these films displayed visible spoilage by the trial's conclusion. In contrast, under refrigerated storage ( $5 \pm 1^\circ\text{C}$ ), which occurred period of 60 days, after which visible rot was displayed, Eucalyptus, 25% showed the highest degradation, potentially due to volatile essential oil components. Whereas Moringa 25% film showed the least degradation, likely due to their high content of antioxidant compounds. These findings highlight the significant influence of both film composition and storage temperature on degradation rates.

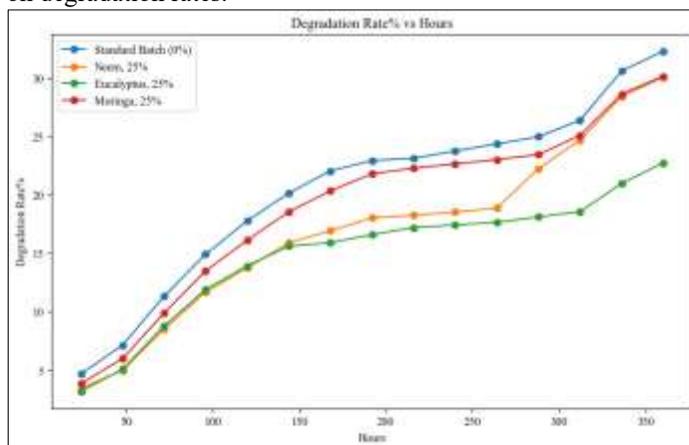


Chart -3 (a): Effect of plant extracts on degradation rate% at room temperature.

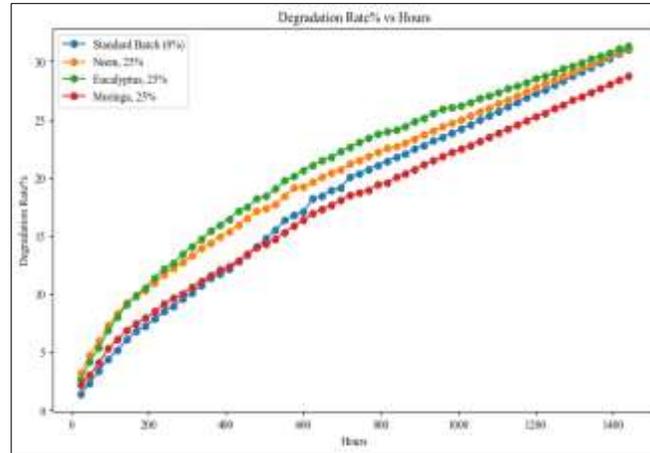


Chart -3 (b): Effect of plant extracts on degradation rate% at refrigerator temperature.

#### 4.7 Soil degradation test

As shown in the Chart-4, four films were evaluated for biodegradation in agricultural soil over six months: Standard Batch (0%), Neem 25%, Eucalyptus 25%, and Moringa 25%. The results revealed distinct degradation patterns, with Eucalyptus 25% exhibiting the highest degradation rate, followed closely by Neem 25%. Moringa 25% showed slightly lower degradation, while the Standard Batch (0%) demonstrated the least weight loss among all tested films. These findings indicate that plant-based additives significantly enhance biodegradation, with Eucalyptus 25% proving most effective in promoting film degradation under soil conditions.

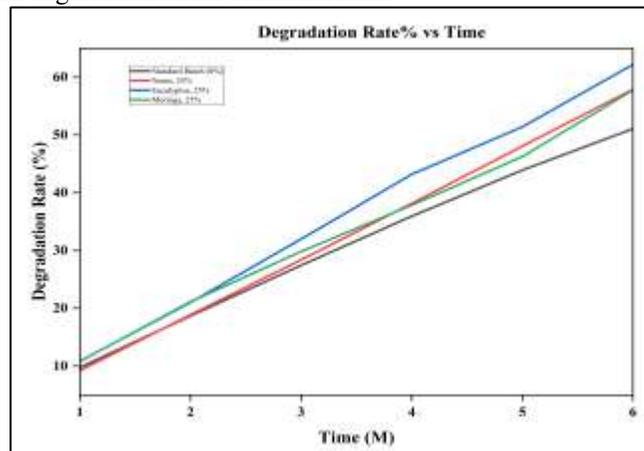


Chart -4: Effect of plant extracts on degradation rate% in soil conditions.

#### 4.8 FOURIER TRANSFORM INFRARED SPECTROSCOPY

As seen in Fig- 7 (a), the standard film exhibited characteristic peaks of a basic polymer matrix, such as C–H stretching near  $2900\text{ cm}^{-1}$  and C=C stretching around  $1730\text{ cm}^{-1}$ , with no significant phytochemical-related absorptions. Whereas as per Fig-7 (b), (c) and (d), FTIR spectra of the Neem, Eucalyptus and Moringa bio-films exhibited additional distinctive peaks not observed in the Standard. Neem, Eucalyptus, and Moringa-based films showed broad O–H bands ( $3200\text{--}3400\text{ cm}^{-1}$ ), C=C aromatic stretches ( $\sim 1600\text{--}1650\text{ cm}^{-1}$ ), and glycosidic C–O peaks ( $\sim 1000\text{--}1200\text{ cm}^{-1}$ ), indicating the presence of flavonoids, tannins, saponins, and other bioactive compounds. N–H bending and C–N stretching ( $\sim 1250\text{--}1350\text{ cm}^{-1}$ ) further confirmed the presence of alkaloids, especially in Neem and Moringa. Terpenoid-associated vibrations ( $\sim 2850\text{--}2950\text{ cm}^{-1}$  and  $\sim 1640\text{--}1680\text{ cm}^{-1}$ ) were evident in Eucalyptus and Moringa films. The presence of these phytochemical-specific absorption bands confirmed the successful integration of plant-derived bioactive constituents into the bio-film matrices.

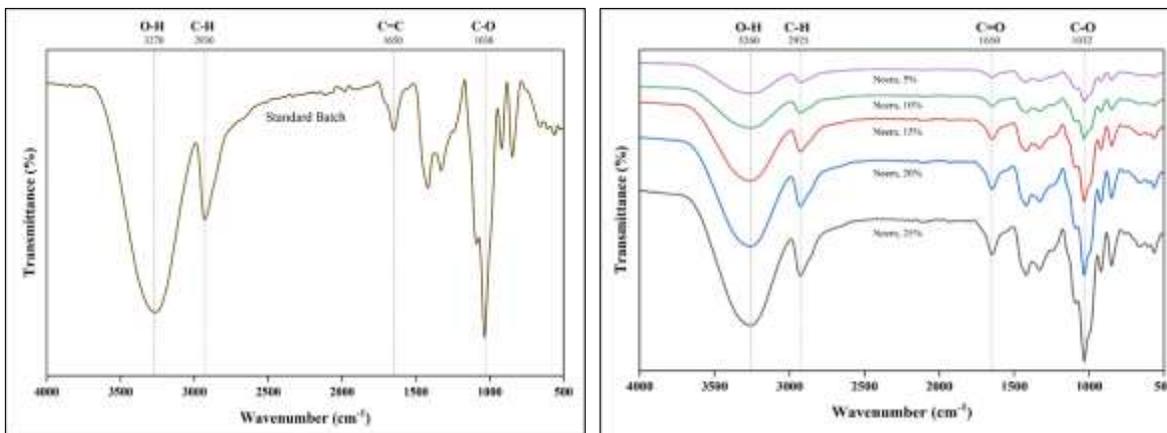


Fig-7: FTIR Spectra of (a) Standard batch film, (b) Neem batch films

(a)

(b)

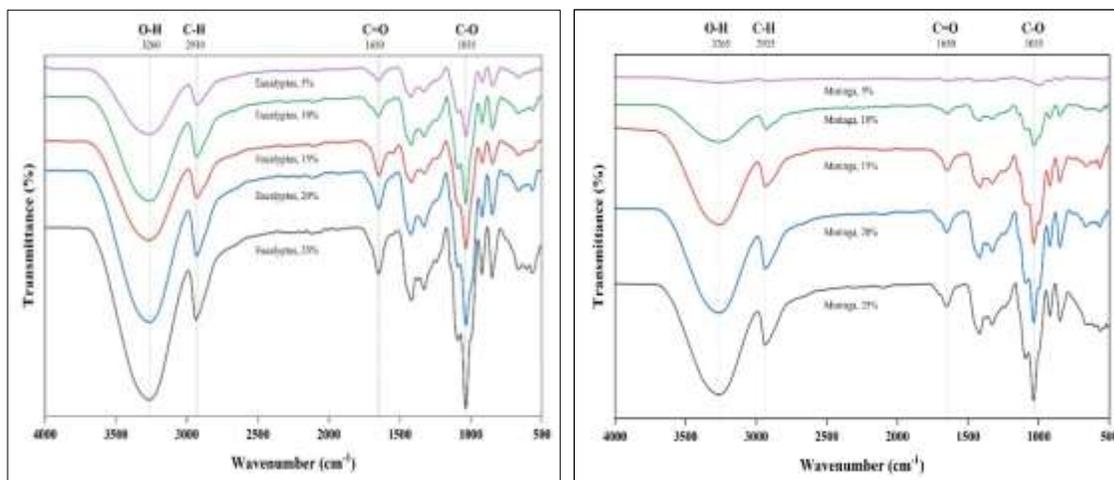


Fig-7: FTIR Spectra of (c) Eucalyptus batch films, (d) Moringa batch films

#### 5. CONCLUSION

This study successfully synthesized biodegradable films using Neem, Eucalyptus, and Moringa leaf extracts within a polyvinyl alcohol-glycerin-starch matrix, with films containing 25% plant extract demonstrating optimal functional properties. Eucalyptus-based films showed the fastest degradation rate in soil, making them ideal for agricultural mulch applications, while grapes packaged in Moringa-based films exhibited minimal degradation under refrigeration, extending their shelf life due to their high antioxidant content. Neem-based films balanced preservation and biodegradability effectively. Phytochemical screening confirmed the presence of bioactive compounds (flavonoids, alkaloids, tannins, terpenoids) in the extracts, with FTIR analysis verifying their integration into the films. Packaging

tests revealed temperature-dependent degradation, with room temperature accelerating spoilage compared to refrigeration, while soil burial tests highlighted enhanced biodegradability in plant extract-infused films, particularly Eucalyptus-based variants. The results demonstrate that Eucalyptus-based films have strong potential for agricultural uses, Moringa-based films are particularly suitable for food packaging applications, and Neem-based films show promise for both agricultural and packaging purposes. Beyond their functional advantages, these plant-based films offer significant environmental benefits by reducing plastic pollution and promoting soil health through natural biodegradation. Economically, they present a sustainable alternative that could decrease dependence on petroleum-based plastics while potentially lowering production costs and creating new market opportunities in the green packaging and agricultural sectors.

## 6. REFERENCES

- [1]. Giulia Fredi, Andrea Dorigato, Compatibilization of biopolymer blends: A review, *Advanced Industrial and Engineering Polymer Research*, 2023, ISSN 2542-5048.
- [2]. A. Ashothaman, J. Sudha, N. Senthilkumar, A comprehensive review on biodegradable polylactic acid polymer matrix composite material reinforced with synthetic and natural fibers, *Materials Today: Proceedings*, Volume 80, Part 3, 2023, Pages 2829-2839, ISSN 2214-7853, <https://doi.org/10.1016/j.matpr.2021.07.047>.
- [3]. Issam Elfalch, Fethi Abbassi, Mohamed Habibi, Furqan Ahmad, Mohamed Guedri, Mondher Nasri, Christian Garnier, A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials, *Results in Engineering*, Volume 19, 2023, 101271, ISSN 2590-1230, <https://doi.org/10.1016/j.rineng.2023.101271>.
- [4]. Lamberti, F.M., Román-Ramirez, L.A. & Wood, J. Recycling of Bioplastics: Routes and Benefits. *J Polym Environ* 28, 2551–2571 (2020). <https://doi.org/10.1007/s10924-020-01795-8>.
- [5]. Muthukumar, V. & Venkatasamy, R. & Mariselvam, V. & Senthilkumar, N. & Fernando, Antony & A, Suresh babu., Comparative Investigation on Mechanical Properties of Natural Fiber Reinforced Polyester Composites. *Applied Mechanics and Materials*. 592-594. 92-96, (2014), doi: 10.4028/www.scientific.net/AMM.592-594.92.
- [6]. Siracusa, Valentina & Blanco, Ignazio., (2020). Bio-Polyethylene (Bio-PE), Bio-Polypropylene (Bio-PP) and Bio-Poly(ethylene terephthalate) (Bio-PET): Recent Developments in Bio-Based Polymers Analogous to Petroleum-Derived Ones for Packaging and Engineering Applications. *Polymers*, 12, 1641, doi: 10.3390/polym12081641.
- [7]. Zhu, Y., Romain, C. & Williams, C. Sustainable polymers from renewable resources. *Nature* 540, 354–362 (2016). <https://doi.org/10.1038/nature21001>.
- [8]. Troy A. Hottle, Melissa M. Bilec, Amy E. Landis, Sustainability assessments of bio-based polymers, *Polymer Degradation and Stability*, Volume 98, Issue 9, 2013, Pages 1898-1907, ISSN 0141-3910, <https://doi.org/10.1016/j.polymdegradstab.2013.06.016>.
- [9]. Seyedeh Fatemeh Mirpoor, Simona Varriale, Raffaele Porta, Daniele Naviglio, Mariachiara Spennato, Lucia Gardossi, C. Valeria L. Giosafatto, Cinzia Pezzella, A biorefinery approach for the conversion of *Cynara cardunculus* biomass to active films, *Food Hydrocolloids*, Volume 122, 2022, 107099, ISSN 0268-005X, <https://doi.org/10.1016/j.foodhyd.2021.107099>.
- [10]. B. Poonkodi, M. Suguna Lakshmi, A. Tamilselvi, C. Sumathi Jones, K. Deepa, Sasikumar Pattabi, H. Bava Bakrudeen, K. Prabhu, Sung Chul Kim, M.S. Ranjith, Bio-nanocomposite films loaded with lemon leaf extract for bio packaging application, *Journal of King Saud University - Science*, Volume 34, Issue 8, 2022, 102333, ISSN 1018-3647, <https://doi.org/10.1016/j.jksus.2022.102333>.
- [11]. Gargi Ghoshal, Deepinderjot Singh, Synthesis and characterization of starch nanocellulosic films incorporated with Eucalyptus globulus leaf extract, *International Journal of Food Microbiology*, Volume 332, 2020, 108765, ISSN 0168-1605, <https://doi.org/10.1016/j.ijfoodmicro.2020.108765>.
- [12]. Yosra Kotb, Orlin D. Velev, Hierarchically reinforced biopolymer composite films as multifunctional plastics substitute, *Cell Reports Physical Science*, 2023, 101732, ISSN 2666-3864, <https://doi.org/10.1016/j.xcrp.2023.101732>.
- [13]. Supalak Manotham, Marut Khieokae, Pichitchai Butnoi, Electrospun biopolymer polyvinyl alcohol/Centella asiatica extract nanofibers for antibacterial activity, *Materials Today: Proceedings*, 2023, ISSN 2214-7853, <https://doi.org/10.1016/j.matpr.2023.06.166>.
- [14]. Jiaoyang Chen, Jiajie Jing, Cheng Wang, Tao Chen, Jianhua Xu, Bowen Yao, Jiajun Fu, Ultra-strong, ultra-tough, and transparent polymer composite with excellent dynamic and biodegradable properties enabled by bicontinuous structure, *Polymer*, Volume 283, 2023, 126220, ISSN 0032-3861, <https://doi.org/10.1016/j.polymer.2023.126220>.

- [15]. Yongseok Ko, Youri Yang, Dockyu Kim, Yong Hwan Lee, Sunil Ghatge, Hor-Gil Hur, Fungal biodegradation of poly(butylene adipate-co-terephthalate)-polylactic acid-thermoplastic starch based commercial bio-plastic film at ambient conditions, *Chemosphere*, Volume 353, 2024, 141554, ISSN 0045-6535, <https://doi.org/10.1016/j.chemosphere.2024.141554>.
- [16]. Kiruthika Parangusan, Venkat Subramaniam, Anandha babu, P. Sundara venkatesh, S. Vijayalakshmi, Deepalekshmi Ponnamma, Biocompatible neem gum-modified polyvinyl alcohol composite as dielectric material for flexible energy devices, *Heliyon*, Volume 10, Issue 7, 2024, e28379, ISSN 2405-8440, <https://doi.org/10.1016/j.heliyon.2024.e28379>.
- [17]. Pandagale, Shweta. (2023). Biodegradable polymer from banana peels for industrial applications [Master's Thesis]. Institute of Chemical Technology, Mumbai.
- [18]. Mhaske, Vikas. (2023). Synthesis of Biodegradable Mulching Film from Biopolymers and Natural Fibers for Agricultural Applications [Master's Thesis]. Institute of Chemical Technology, Mumbai.
- [19]. S. Taweechaisupapong, W. Pinsuwan, W. Suwannarong, R. Kukhetpitakwong, S. Luengpailin, Effects of *Streblus asper* leaf extract on the biofilm formation of subgingival pathogens, *South African Journal of Botany*, Volume 94, 2014, Pages 1-5, ISSN 0254-6299, <https://doi.org/10.1016/j.sajb.2014.05.005>.
- [20]. Raisa N. Chodankar, Raghunath Patil, Sumati A. Hogade, Anandkumar G. Patil, Aditya Acharya, Evaluation of *Mangifera indica*, *Anacardium occidentale* leaf extracts and 0.2% Chlorhexidine gluconate on disinfection of maxillofacial silicone material surface contaminated with microorganisms - An invitro study, *Journal of Oral Biology and Craniofacial Research*, Volume 14, Issue 3, 2024, Pages 301-306, ISSN 2212-4268, <https://doi.org/10.1016/j.jobcr.2024.03.014>.