EPJ Web of Conferences **347**, 04002 (2026) https://doi.org/10.1051/epjconf/202634704002
SCMERD 2025

Development and evaluation of biodegradable seedling tubes from beeswax and macadamia nut composites

Thandiwe Chisi [1], *Mark* Msiska[1], *Haleema* Amasi[1], *Alfred* Levison[1], *Blessings* Masina[1,2*], *Vincent* Mwale[3] *and Richard* Nkhoma[1]

[1]Department of Engineering, Malawi University of Science and Technology, Thyolo, Malawi
[2]Department of Environmental Engineering, Bandung Institute of Technology, Bandung, Indonesia
[3]Department of Energy Systems, Mzuzu University, Private Bag 201, Mzuzu, Malawi

Abstract. This study investigates the development of biodegradable seedling tubes using macadamia nutshell powder as a filler and beeswax as a natural binder, to provide a sustainable alternative to conventional polyethene tubes. A total of twenty-four experimental runs were conducted following a Design of Experiments framework to evaluate the effects of beeswax–to–macadamia ratios (90:10, 70:30, and 50:50 wt %), soil pH, temperature, and moisture content on biodegradability over a 28-day soil burial test. Elemental composition was determined by X-ray fluorescence analysis, while statistical significance was assessed using analysis of variance. Results showed that biodegradation rates ranged from 28.2% to 58.3%, with the beeswax ratio exerting the most significant influence ($p < 0.05$) on degradation behaviour, followed by temperature and soil moisture. Tubes with higher beeswax content exhibited greater structural stability and water resistance but lower biodegradability. Conversely, lower beeswax ratios favoured faster microbial decomposition. Elemental analysis revealed appreciable levels of SiO2, Al2O3, and Fe2O3, which contribute to mechanical stability and may facilitate micronutrient enrichment during decomposition. The findings confirm the technical feasibility of producing biodegradable, plantable seedling tubes from locally available agro-wastes. The composite formulation offers an environmentally sound, low-cost alternative to plastic seedling containers while supporting circular-economy principles and promoting sustainable nursery management practices in Malawi and similar contexts.

1 Introduction

Plastics have been among the most transformative materials in modern history. According to the International Union of Pure and Applied Chemistry (IUPAC), plastics are polymeric materials that may contain other substances to improve performance and reduce costs. Since their invention in the late nineteenth century and the onset of industrial production in 1907, global plastic output has grown exponentially, from approximately 2 million tonnes in 1950 to over 400 million tonnes in 2022 [1, 2].

Their versatility, durability, and affordability have revolutionised manufacturing and agriculture, but their environmental consequences have become increasingly severe. Each year, an estimated 19–23 million tonnes of plastic waste enter aquatic ecosystems, polluting rivers, lakes, and oceans [3]. The persistence of plastics in the environment disrupts habitats, reduces ecosystem resilience, and leads to the formation of microplastics that enter food chains and water systems, posing risks to both biodiversity and human health [4]. Microplastic particles have been detected in municipal water supplies, human blood, and lung tissue, indicating the pervasiveness of plastic contamination and its long-term implications for global health.

In response to these challenges, the international community has moved from reliance on recycling towards strategies aimed at reducing and replacing single-use plastics. More than 150 municipalities in the United States have implemented bans or levies on plastic bags since 2014, while the European Parliament legislated to phase out a wide range of single-use plastics by 2021 [5]. Similar measures have been adopted across Africa, with approximately 30 countries now enforcing bans on single-use plastic bags. In Malawi, a ban on thin plastics was introduced in 2015, but legal disputes initiated by plastic manufacturers delayed enforcement. The High Court's ruling of 31 January 2025, which lifted the injunctions against implementation, represents a significant step forward in the country's efforts to combat plastic pollution [5, 6].

Despite these regulatory efforts, plastic waste remains a major environmental issue in Malawi. The widespread use of single-use plastics, particularly in packaging and agricultural applications, continues to contribute to clogged drainage systems, flooding, and declining soil fertility. According to the United Nations Development Programme [6], Malawi generates approximately 75,000 tonnes of plastic annually, of which nearly 80% is single-use and non-recyclable. The shift by beverage producers from returnable glass to plastic bottles and the use of thin plastic bags by informal traders have exacerbated the problem. In addition to its impacts on terrestrial and aquatic environments, plastic waste affects agricultural productivity by hindering root penetration and reducing water infiltration. Moreover, plastic production and incineration contribute to significant greenhouse gas emissions, with the sector estimated to account for over 15% of methane emissions from landfills globally [7].

At the same time, Malawi's agricultural sector continues to underutilise valuable natural resources such as beeswax and macadamia nut shells. Beeswax, a by-product of apiculture, is commonly discarded despite its potential as a biodegradable, hydrophobic, and nutrient-

---

* Corresponding author: bmasina@must.ac.mw

rich binder. Macadamia nut shells, which are rich in lignocellulosic compounds, are largely considered waste despite their high structural integrity and slow degradation rate. Harnessing these underexploited materials offers an opportunity to develop sustainable alternatives to petrochemical plastics, create new revenue streams for rural communities, and promote circular economy practices.

This study addresses the dual challenges of plastic pollution and agricultural waste management by developing biodegradable seedling tubes made from beeswax and macadamia nut shell powder. These tubes are designed to replace conventional polyethylene seedling containers widely used in nursery operations, which are non-biodegradable and contribute to environmental degradation. Conventional polythene tubes have additional drawbacks, including root coiling, restricted root aeration, and transplant shock, which compromise seedling growth and survival [8]. The development of biodegradable seedling containers offers a promising solution to these limitations, enabling seedlings to be planted directly with the container, thus reducing root disturbance and labour during transplanting.

This work aims to utilise locally available beeswax and macadamia nut shell waste to produce biodegradable seedling tubes as a sustainable replacement for polythene tubes. Specifically, the study analyses the elemental composition of beeswax and macadamia nut shells to determine their suitability for composite formation, establishes the optimal beeswax-to-shell ratio for structural integrity and biodegradability, and evaluates the influence of temperature, pH, and moisture on the degradation rate of the tubes. By integrating local agricultural by-products into functional materials, this research advances environmentally responsible production systems, supports Malawi's national efforts to eliminate thin plastics, and contributes to the global agenda for sustainable materials and waste reduction.

2 Literature Review

Biodegradable planting containers have been investigated using a range of natural materials; research on the combined use of beeswax and nutshell waste remains limited. Most previous studies have focused on starch-based systems or fibre–polymer composites, with little emphasis on hydrophobic natural binders. Furthermore, many biodegradable formulations degrade too rapidly in humid environments or lack sufficient mechanical strength for handling during the nursery phase [9].

The environmental consequences of non-biodegradable plastics have intensified interest in developing sustainable materials for agricultural applications. Plastics have become indispensable in modern agriculture due to their versatility, low cost, and ability to enhance productivity through applications such as mulching, greenhouse covers, irrigation systems, and seedling containers [10]. However, their durability and resistance to degradation, once considered advantageous, have now emerged as their most problematic traits. The global accumulation of agricultural plastic waste poses severe threats to soil health, biodiversity, and climate resilience [11].

2.1 Plasticulture and Environmental Impact

The integration of plastics into agriculture, commonly referred to as plasticulture, has increased crop yields and resource-use efficiency. Yet, the end-of-life phase of plastic materials remains poorly managed, particularly in low-income regions where waste collection and recycling infrastructure are limited [12]. Agricultural plastics often fragment into microplastics (MPs) and nanoplastics (NPs) via photodegradation and mechanical weathering, thereby contaminating soil and water bodies [13]. These particles can adsorb toxic compounds, disrupt soil microbial balance, and interfere with plant nutrient uptake [14]. Studies show that MPs in agricultural soils can alter enzymatic activity, reduce organic carbon cycling, and impede seed germination [11].

The environmental persistence of conventional seedling containers is particularly concerning. Seedlings are typically raised in polythene tubes made from petroleum-derived polymers such as polyethylene (PE) or polypropylene (PP). These materials are inexpensive and durable, but they pose several agronomic and ecological disadvantages. Their smooth inner surfaces restrict root expansion, leading to coiling and deformation, which reduce root anchorage and plant vigour after transplanting [8]. Once seedlings are transplanted, these tubes are discarded and accumulate in soils and waterways, blocking drainage systems and creating breeding grounds for pests [15, 16]. The persistence of these plastics has prompted policy measures, including taxes and outright bans, to reduce their use [17].

2.2 Advances in Biodegradable Containers

The search for environmentally responsible alternatives has driven research into biodegradable and compostable materials derived from renewable biomass. These include starch, cellulose, lignin, natural oils, and protein-based polymers [18, 19]. Biodegradable seedling containers decompose naturally under microbial action, eliminating the need for removal during transplanting and thereby reducing root disturbance and labour costs [9].

Early innovations in this area include Jiffy pots, first commercialised in the 1950s, which were produced from compressed peat and wood pulp [20]. These containers degraded readily after transplantation and allowed root penetration, although their cost and reliance on non-renewable peat limited widespread adoption [21]. More recent studies have explored containers made from agricultural residues such as rice husk, cassava peel, and tomato waste [22, 23]. For example, biodegradable nursery containers composed of rice husk and modified cornstarch adhesives demonstrated improved water resistance and strength, but formulations containing synthetic additives such as urea–formaldehyde exhibited slower degradation and environmental compatibility issues [22].

Schettini et al [23] developed biodegradable tubes from tomato and hemp fibres bound with sodium alginate. The resulting biocomposite exhibited good mechanical integrity but was highly sensitive to moisture, leading to premature softening under wet conditions. Scanning electron microscopy (SEM) analysis revealed an irregular fibre distribution and the presence of voids, which weakened the structure and led to inconsistent degradation [23]. These findings highlight the delicate balance required between mechanical stability and biodegradability in the design of effective plantable containers.

2.3 Material Considerations for Biodegradable Composites

The selection of raw materials strongly influences the functional and environmental performance of biodegradable composites. Ideal seedling containers should maintain structural integrity during the nursery phase, resist excessive moisture absorption, and degrade predictably once transplanted. Lignocellulosic agricultural wastes such as rice husk, coconut shell, and nutshells are attractive as fillers because of their high lignin and cellulose content, which confer rigidity and toughness [24]. However, the hydrophilic nature of many natural polymers requires modification or blending with hydrophobic agents to improve water resistance.

Beeswax is emerging as a promising natural binder in biodegradable composites. It is biodegradable, hydrophobic, and possesses a relatively high melting point (60–65 °C), providing thermal and structural stability in warm nursery environments. Studies have shown that beeswax enhances the water barrier and mechanical properties of starch-based and fibre-based composites [25]. Paula et al. [24] demonstrated that combining beeswax with roasted cashew nutshell powder produced dense, durable seedling tubes with improved water resistance and biodegradability. These composites performed favourably compared with polypropylene tubes in seedling growth trials and could be directly planted in soil, thereby minimising transplant stress.

Macadamia nut shells are another underutilised agro-industrial residue with significant potential for developing biodegradable composites. They contain high levels of lignin, cellulose, and silica, which provide mechanical reinforcement and slow biodegradation [26]. When finely ground, macadamia shell powder acts as a filler that enhances stiffness while providing micronutrients, including calcium, magnesium, and potassium, during decomposition. Integrating macadamia shell powder with beeswax as a binder can produce a balanced composite that offers both durability and controlled degradability under soil conditions.

3 Materials and Methods

3.1 Materials

Natural beeswax, used as a biodegradable binder, was sourced from local beekeepers in Lilongwe, Malawi. Macadamia nut shells were collected from Conforzi Plantations Ltd (Thyolo, Malawi), while fresh cow dung served as a microbial inoculum for the biodegradation tests. Sodium bicarbonate and vinegar were used to regulate soil pH during the experiments. All chemicals were of analytical grade and used without further purification.

The principal raw materials, beeswax and macadamia nut shells, were selected based on their abundance, biodegradability, and complementary physicochemical properties. Beeswax provides hydrophobicity and mechanical cohesion, whereas macadamia nut shells, rich in lignin, cellulose, and silica, confer rigidity and controlled degradation behaviour.

3.2 Preparation of Raw Materials

Macadamia nut shells were washed with water and dried in sunlight for 48 hours. The dried shells were ground with a mechanical grinder and sieved to obtain a powder with a particle size less than 100 μm. The resulting macadamia nutshell powder (MNSP) was stored in airtight containers before use.

Beeswax was cut into small pieces to facilitate melting and was stored at room temperature. Before mixing, both components were weighed to ensure accurate formulation ratios.

3.3 Elemental Characterisation

Elemental composition was determined using X-ray fluorescence (XRF) spectroscopy to assess the presence of oxides and trace elements relevant to mechanical stability and biodegradability. Approximately 4 g of each powdered sample, beeswax, and macadamia nut shells were loaded into XRF sample cups lined with X-ray-transparent film and analysed using a calibrated Spectro Xepos spectrometer. Calibration was performed with a certified reference material to ensure analytical accuracy. The analysis provided quantitative data on principal oxides (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, K_2O) and trace metals, confirming environmental safety and compositional suitability for composite formulation.

3.4 Fabrication of Biodegradable Seedling Tubes

Biodegradable seedling tubes were fabricated by combining molten beeswax with macadamia nutshell powder at three mass ratios: 90:10, 70:30, and 50:50 (beeswax: MNSP). Beeswax was melted in a double-boiler to prevent thermal degradation and ensure uniform heating. Once liquefied, the macadamia powder was gradually added while the mixture was stirred continuously with a mechanical mixer to ensure homogeneity.

The mixture was immediately poured into cylindrical moulds pre-coated with a thin layer of release agent. Gentle tapping was applied to remove trapped air and enhance compaction. The moulded samples were left to cool at ambient temperature for approximately 50 minutes before demoulding. A total of twenty-four tubes were produced according to the experimental design, representing the whole combination of composition and environmental variables. The tubes were then air-dried under laboratory conditions before testing.

3.5 Experimental Design

A Design of Experiments (DOE) approach based on the Box–Behnken design was used to investigate the influence of four independent variables, beeswax content (B), soil pH (A), temperature (C), and moisture content (D), on the biodegradation rate of the composite tubes. Each factor was studied at three levels (low, medium, and high), coded as −1, 0, and +1. This statistical approach allowed simultaneous evaluation of individual and interactive effects on the response variable (biodegradation rate).

The DOE generated 24 runs, enabling efficient exploration of factor interactions while minimising the number of experimental trials. The response variable was expressed as percentage mass loss after 28 days of soil burial, representing the degree of biodegradation.

3.6 Data Analysis

Biodegradability was assessed using a soil burial test adapted from the standard method ISO 846. Tubes were weighed to determine their initial mass (Wi), then coated with a thin layer of cow dung to facilitate microbial inoculation. Each sample was buried 2 cm deep in 1 kg of soil contained in a 1.5 L plastic vessel. Soil conditions were adjusted according to the DOE matrix to achieve the desired pH, temperature, and moisture levels.

The burial tests were conducted over 28 days, with periodic moisture adjustment to maintain consistent conditions. At the end of the test period, the samples were carefully exhumed, washed with deionised water to remove soil residues, and air-dried for 48 hours before reweighing. The biodegradation rate (W%) was calculated as:

$$W(\%) = \frac{W_i - W_f}{W_i} \times 100 \qquad (1)$$

where W_i is the initial mass and W_f the final mass after burial.

All experimental data were analysed using analysis of variance (ANOVA) to evaluate the statistical significance of each factor and its interactions. The adequacy of the fitted model was assessed through F-values, p-values, and correlation coefficients. Response surface and contour plots were generated to visualise the interaction effects between the variables and to identify the optimal combination of factors that maximise biodegradability.

4 Results

4.1 Elemental Composition of Raw Materials

The samples exhibited differences in colour, texture, and surface smoothness corresponding to beeswax content. Fig 1 shows a sample of the manufactured biodegradable seedling tubes.

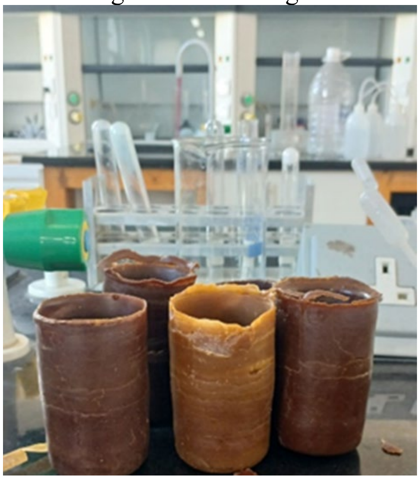

Fig. 1. Fabricated biodegradable seedling tubes produced from beeswax–macadamia nutshell composites at varying composition ratios (90:10, 70:30, and 50:50 w/w).

The XRF analysis of the macadamia nutshell powder (MNSP) revealed the presence of principal oxides, including SiO_2 (2.78 %), Al_2O_3 (1.53 %), and Fe_2O_3 (0.67 %), which are typically associated with structural reinforcement and thermal stability in lignocellulosic materials. Secondary oxides such as CaO (0.33 %), MgO (0.14 %), and K_2O (0.41 %) were also detected and may confer potential agronomic value during biodegradation. Trace elements, including Zn (19.9 ppm), Cu (19.7 ppm), and Mn (209.5 ppm), were present, indicating micronutrient potential, whereas toxic metals such as arsenic, mercury, and lead were below detection limits.

Beeswax exhibited a similar pattern of oxide constituents, dominated by SiO_2 (3.57 %), Al_2O_3 (1.69 %), and MgO (0.49 %). The presence of Na2O (0.29 %) and P_2O_5 (0.08 %) suggests compatibility with microbial activity, while trace quantities of Fe_2O_3 (0.08 %) and TiO_2 (80.5 ppm) were detected. No significant levels of toxic heavy metals were observed. Collectively, these findings confirm that both materials are environmentally benign and suitable for fabricating biodegradable composites.

4.2 Biodegradation Behaviour

Biodegradability was quantified through the 28-day soil burial test, expressed as percentage mass loss relative to the initial weight. The biodegradation rates across all 24 experimental runs ranged from 28.2 % to 58.3 %. The highest degradation occurred in samples containing 50 % beeswax and 50 % MNSP, particularly under conditions of high moisture (≈ 90 %) and elevated temperature (≈ 30 °C). In contrast, tubes containing 90 % beeswax exhibited the lowest mass loss, demonstrating greater water resistance and structural stability.

The analysis of variance (ANOVA) confirmed that the quadratic model used to predict biodegradability was statistically significant, with an F-value of 17.59 and a p-value < 0.0001, indicating strong correlation between the experimental factors and the degradation response. Among the independent variables, beeswax ratio showed the highest influence ($p < 0.05$), followed by temperature and moisture content, whereas soil pH exhibited a comparatively minor effect within the studied range (6.0–8.5).

4.3 Response Surface Analysis

Response surface plots revealed clear interaction effects among key variables. As shown in Fig. 2, the interaction between beeswax content and temperature showed that biodegradability increased with decreasing beeswax content and increasing temperature. Similarly, as shown in Fig. 3, the interaction between beeswax content and moisture demonstrated that high moisture levels accelerated degradation at lower beeswax concentrations but had minimal impact at higher wax levels.

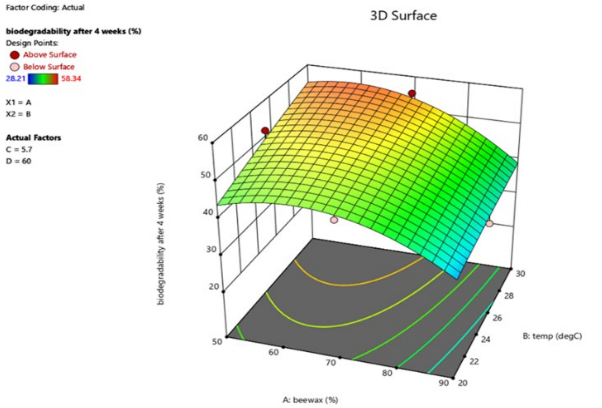

Fig. 2. Response surface plot showing the interaction effect of beeswax content and temperature on biodegradation rate after 28 days.

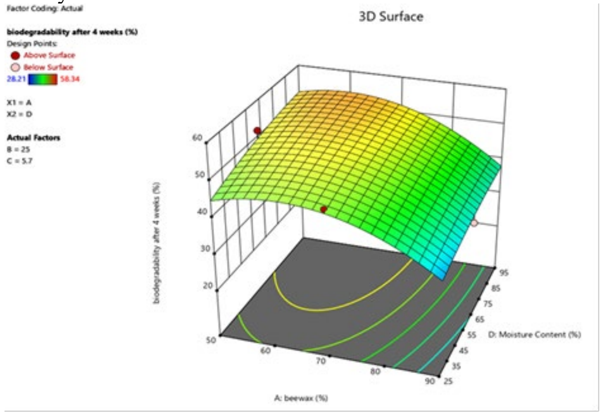

Fig. 3. Response surface plot illustrating the combined effect of beeswax content and soil moisture on biodegradability

The optimisation analysis (as shown in Fig. 4) identified the most favourable conditions for biodegradation as follows: beeswax content = 50 %, temperature = 29.9 °C, pH = 7.1, and moisture content = 88 %. Under these conditions, the model predicted a maximum biodegradation rate of approximately 58.3 % after 28 days, consistent with experimental observations.

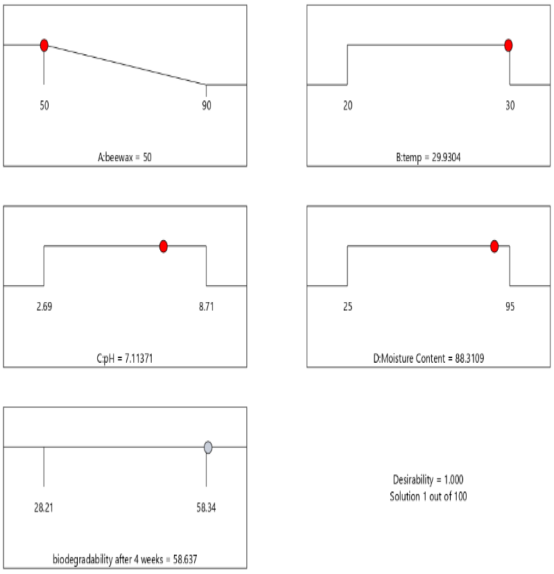

Fig 4. Optimisation plot indicating the predicted biodegradation rate under varying experimental conditions

4.4 Physical Characteristics of Tubes

Visual and tactile inspection showed that tubes with higher beeswax proportions (70–90 %) were more robust, exhibited a smoother surface finish, and maintained dimensional integrity throughout the soil burial period. Conversely, tubes with 50 % beeswax content showed partial disintegration after three weeks, accompanied by surface roughening and fragmentation, indicative of microbial degradation. No significant odour or fungal overgrowth was observed, suggesting natural decomposition rather than contamination-driven decay.

5 Discussion

The elemental composition results confirm that both beeswax and macadamia nutshell powder are environmentally safe and suitable for developing biodegradable composites. The presence of silica (SiO_2) and alumina (Al_2O_3) in both materials contributes to their mechanical strength and thermal resistance [27]. Meanwhile, oxides of calcium, magnesium, and potassium are beneficial during decomposition, releasing nutrients that can improve soil fertility. The absence of hazardous elements such as lead, mercury, and arsenic supports the ecological compatibility of the developed material for agricultural applications.

These compositional characteristics align with earlier findings that lignocellulosic residues reinforced with natural binders provide both structural integrity and nutrient release upon degradation [28]. Beeswax, in particular, acts as a natural hydrophobic agent, enhancing cohesion and water-absorption resistance, which are critical parameters for seedling-tube performance in humid environments.

The biodegradation results show a clear dependence on both material composition and environmental conditions. The slower degradation at higher beeswax ratios (≥ 70 %) can be attributed to the hydrophobic and crystalline nature of beeswax, which limits water penetration and microbial access to the organic matrix. Similar effects have been reported in wax-modified starch composites, in which high hydrophobicity delays enzymatic degradation [29]. Conversely, at lower beeswax contents (50 %), increased exposure of lignocellulosic filler promotes microbial colonisation, leading to accelerated mass loss.

Temperature and moisture exhibited synergistic effects, with higher levels of both promoting faster degradation. Elevated temperatures (~30 °C) enhance microbial metabolism and enzymatic activity, while moisture facilitates diffusion of enzymes and oxygen through the matrix. These findings correspond to previous studies indicating that biodegradation in soil environments is maximised under warm and moist conditions [30]. The limited influence of pH within the studied range may mean that most soil microorganisms involved in lignocellulosic degradation are tolerant to near-neutral environments.

The statistical model's high F-value and low p-value validate the experimental design and indicate reliable predictive capacity. The observed interactions between beeswax ratio and environmental variables reflect a balance between structural stability and degradation rate, a common trade-off in biodegradable composite design [31].

The maximum observed biodegradation rate of 58.3 % after 28 days compares favourably with values reported for similar biocomposites. According to the French specification (NF U52-001), the criteria for soil biodegradability are defined as a minimum of 60% and a maximum of 90% for soil (12-month period) and compost media (6-month period), respectively [32]. Although the tubes have not yet reached the 60% threshold for soil biodegradation, their 28-day performance indicates promising short-term biodegradability, suggesting they are on track to meet the French standard over the long term [32].

The observed balance between durability and degradability positions the beeswax–macadamia formulation within the "plantable" category of biodegradable containers, as described by [33]. Such materials maintain integrity during nursery handling yet decompose sufficiently once in soil, promoting root penetration and reducing transplant shock. Furthermore, both raw materials are locally available in Malawi, offering a cost-effective and sustainable pathway to substitute imported or synthetic seedling tubes.

The material's degradation profile means suitability for short-term nursery use (2–4 weeks), followed by gradual decomposition after planting. Improvements in mould design and mixing uniformity should be considered to ensure consistent wall thickness and reduce brittleness at lower beeswax contents. Future studies should incorporate mechanical strength testing, water absorption measurements, and microstructural characterisation (SEM) to validate the composite's performance further. Long-term soil trials across varying climatic regions in Malawi would also provide insight into seasonal effects on degradation kinetics and plant growth performance.

6 Conclusion

This study has shown the technical feasibility of producing biodegradable seedling tubes from beeswax and macadamia nutshell powder, which is an environmentally sustainable alternative to conventional polyethylene containers widely used in nursery operations. The XRF analysis confirmed that both materials are free of toxic elements and contain beneficial oxides, such as SiO2, Al2O3, and CaO, which contribute to structural stability and may facilitate nutrient enrichment during degradation.

The soil burial tests revealed biodegradation rates ranging from 28.2 % to 58.3 % over 28 days, with degradation strongly influenced by beeswax content, temperature, and moisture. Tubes containing 50 % beeswax exhibited the highest biodegradation under warm, moist conditions, whereas those with higher wax content retained greater structural integrity but degraded more slowly. The statistical model developed through ANOVA and response surface analysis confirmed that beeswax ratio is the most significant factor affecting biodegradability, followed by temperature and moisture.

The results indicate that optimising the beeswax–macadamia composition can balance durability during nursery use with biodegradability after transplanting, thereby eliminating the need for plastic removal and reducing environmental waste. The approach also valorises locally available agricultural residues, supporting circular economy principles and green manufacturing in Malawi.

Future research should focus on mechanical property testing, microstructural analysis, and field validation to refine performance and assess the feasibility of large-scale production. Overall, this work provides a viable pathway for transitioning from petroleum-based nursery materials to sustainable, locally derived biocomposites that align with national and global sustainability goals.

References

1. N. T. Pilapitiya, P. G. C., A. S. Ratnayake, The world of plastic waste: A review. Clean. Mater. **11**, 100220 (2024). https://doi.org/10.1016/j.clema.2024.100220
2. A. Rafey, F. Z. Siddiqui, A review of plastic waste management in India – challenges and opportunities. Int. J. Environ. Anal. Chem. **103**(16), 3971–3987 (2023). https://doi.org/10.1080/03067319.2021.1917560
3. UNEP Programme, Plastic Pollution. (2023). https://www.unep.org/plastic-pollution
4. L. Parker, Microplastics are in our bodies. How much do they harm us? Natl. Geogr. (2023). https://www.nationalgeographic.com/environment/article/microplastics-are-in-our-bodies-how-much-do-they-harm-us

5. J. Turpie, G. L., Y. Ng'oma, K. Moore, The case for banning single-use plastics in Malawi. Anchor Environmental Consultants Report No. AEC/1836/1, 64 pp. (2019). https://www.lilongwewildlife.org/wp-content/uploads/The-Case-for-Banning-Single-Use-Plastics-Report-in-Malawi.pdf
6. R. Mweninguwe, Malawi's journey towards a plastic-free future. (2025). https://www.dandc.eu/en/article/after-years-legal-disputes-malawi-has-enforced-ban-thin-single-use-plastics-challenge-now
7. K. Vasarhelyi, The impact of plastic on climate change. (2023). https://www.colorado.edu/ecenter/2023/12/15/impact-plastic-climate-change
8. J. K. Muriuki, A. W. Kuria, C. W. Muthuri, A. Mukuralinda, A. J. Simons, R. H. Jamnadass, Testing biodegradable seedling containers as an alternative for polythene tubes in tropical small-scale tree nurseries. Small-scale For. **12**(3) (2013). https://doi.org/10.1007/s11842-013-9243-8
9. K. M. L. Wilkinson, T. D. Thomas, D. L. Haase, B. F. Daley, R. K. Dumroese, Tropical Nursery Manual: A Guide to Starting and Operating a Nursery for Native and Traditional Plants. U.S. Dept. Agric., Forest Service (2014). https://www.fs.usda.gov/rm/pubs_series/wo/wo_ah732.pdf
10. T. Hofmann, S. Ghoshal, N. Tufenkji, J. F. Adamowski, S. Bayen, Q. Chen, P. Demokritou, M. Flury, T. Hüffer, N. P. Ivleva, R. Ji, R. L. Leask, M. Maric, D. M. Mitrano, M. Sander, S. Pahl, M. C. Rillig, T. R. Walker, J. C. White, K. J. Wilkinson, Plastics can be used more sustainably in agriculture. Commun. Earth Environ. 4 (2023). https://doi.org/10.1038/s43247-023-00982-4
11. Y. Cheng, W. Song, H. Tian, K. Zhang, B. Li, Z. Du, W. Zhang, J. Wang, J. Wang, L. Zhu, The effects of high-density polyethylene and polypropylene microplastics on the soil and earthworm Metaphire guillelmi gut microbiota. Chemosphere **267**, 129219 (2021). https://doi.org/10.1016/j.chemosphere.2020.129219
12. FAO, Assessment of agricultural plastics and their sustainability: A call for action. FAO (2021). https://doi.org/10.4060/cb7856en
13. A. Lakhiar, H. Yan, J. Zhang, G. Wang, S. Deng, R. Bao, C. Zhang, T. N. Syed, B. Wang, R. Zhou, X. Wang, Plastic Pollution in Agriculture as a Threat to Food Security, the Ecosystem, and the Environment: An Overview. Agronomy **14**(3) (2024). https://doi.org/10.3390/agronomy14030548
14. E.-L. Ng, E. Huerta Lwanga, S. M. Eldridge, P. Johnston, H.-W. Hu, V. Geissen, D. Chen, An overview of microplastic and nanoplastic pollution in agroecosystems. Sci. Total Environ. **627**, 1377–1388 (2018). https://doi.org/10.1016/j.scitotenv.2018.01.341
15. Strange, M. Strange, Plastic bags – policies and practices to reduce consumption: Assessing the application of policies to lightweight single-use polyethylene plastic bags. Residua Limited (2008). https://www.acrplus.org/global/gene/link.php?doc_id=227&fg=1
16. Adane, D. Muleta, Survey on the usage of plastic bags, their disposal and adverse impacts on environment: A case study in Jimma City, Southwestern Ethiopia. J. Toxicol. Environ. Health Sci. **3**(8), 234-248 (2011).
17. ACR+, Plastic Bags – Policies and Practices to Reduce Consumption. (2008). https://www.acrplus.org/global/gene/link.php?doc_id=227&fg=1
18. S. Brockhaus, M. Petersen, W. Kersten, A crossroads for bioplastics: exploring product developers' challenges to move beyond petroleum-based plastics. J. Clean. Prod. **127**, 84–95 (2016). https://doi.org/10.1016/j.jclepro.2016.04.003
19. N. O. Alobi, E. A. Sunday, T. O. Magu, G. O. Oloko, B. E. Nyong, Analysis of starch from non-edible root and tubers as sources of raw materials for the synthesis of biodegradable starch plastics. J. Basic Appl. Res. **3**(1) (2017).
20. Jiffy, Home Gardening-A Heritage of Innovation. (n.d.). https://jiffygroup.com/jiffy-home-gardening/
21. A. Khan, T. Mahmood, B. Bano, Development of bio-decomposable (Jiffy) pots for raising and transplanting nursery plants. Int. J. Agric. Biol. **2**(4), 380–381 (2000).
22. E. Sun, H. Huang, F. Sun, G. Wu, Z. Chang, Degradable Nursery Containers Made of Rice Husk and Cornstarch Composites. BioResources **12**, 785–798 (2016). https://doi.org/10.15376/biores.12.1.785-798
23. E. Schettini, G. Santagata, M. Malinconico, B. Immirzi, G. Scarascia Mugnozza, G. Vox, Recycled wastes of tomato and hemp fibres for biodegradable pots: Physico-chemical characterisation and field performance. Resour. Conserv. Recycl. **70**, 9–19 (2013). https://doi.org/10.1016/j.resconrec.2012.11.002
24. Y. Paula, R. Melo, E. Paula, E. R. Morais, F. Junior, A. Pimenta, F. Rusch, M. Scatolino, T. Pedrosa, Seedling Production in Eco-Friendly Tubes Manufactured with Beeswax and Cashew Nutshell. Forests **15**, 2228–2236 (2024). https://doi.org/10.3390/f15122228
25. Mohanty, S. P. Mohanty, Effect of beeswax on the physical and mechanical properties of solution cast poly(butylene adipate co-terephthalate)/thermoplastic starch/beeswax films. J. Elastomers Plast. **55**(3), 400–408 (2023). https://doi.org/10.1177/00952443221150767
26. S. Khan, M. M. Islam, J. Epaarachchi, S. Shibata, Exploring the Prospects of Macadamia Nutshells for Bio-Synthetic Polymer Composites: A Review.

Polymers **15**(19), 4007 (2023). https://doi.org/10.3390/polym15194007

27. A. Ali, N. Zhang, R. M. Santos, Mineral Characterization Using Scanning Electron Microscopy (SEM): A Review of the Fundamentals, Advancements, and Research Directions. Appl. Sci. **13**(23), 12600 (2023). https://doi.org/10.3390/app132312600
28. L. R. Kumar, S. Palaniappan, M. Ramesh, S. M R, S. Siengchin, Assessment of biodegradation of lignocellulosic fibre-based composites – A systematic review. Int. J. Biol. Macromol. **253**, 127237 (2023). https://doi.org/10.1016/j.ijbiomac.2023.127237
29. S. Niu, W. He, Q. Chang, X. Deng, Y. Xie, Beeswax-Modified Starch–Cellulose Composites with Superhydrophobic and Self-Cleaning Capability. Starch-Stärke **75** (2023). https://doi.org/10.1002/star.202200285
30. D. Mishra, I. Saxena, A. Gupta, P. Yadav, Soil Properties as Key Determinants for the Biodegradation Kinetics of Polymer Blends in Indian Agroecosystems. Asian J. Chem. **37**(10), 2477–2486 (2025). https://doi.org/10.14233/ajchem.2025.34390
31. D. Fouad, M. Farag, Design for Sustainability with Biodegradable Composites. In (2019). https://doi.org/10.5772/intechopen.88425
32. D. Briassoulis, A. Mistriotis, B. D. Wilde, D. Noord, Standard testing methods and specifications for biodegradation of bio-based materials in soil - a comparative analysis. Proceedings of the International Conference of Agricultural Engineering, Zurich, Ref C. **668**. (2014).
33. Z. Hussein, Q. Yuan, S. Luo, C. Xu, S. G. Gouda, Plantable Biodegradable Pots as a Cleaner Product from Biomaterials: Characterization and Optimization of Physical and Mechanical Properties. Arab. J. Sci. Eng. **49**(7), 9099–9109 (2024). https://doi.org/10.1007/s13369-023-08550-w