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Biodegradable or Not? Investigating Degradation Under Simulated Indian Storage and Disposal Environments

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Abstract: ***With over 400 million tonnes of plastic garbage produced worldwide per year, a great amount of it stays in the environment for millennia (UNEP 2024), plastic pollution poses a threat to ecosystems and human health. With little infrastructure for recycling and safe disposal, India alone produces over 3.5 million tonnes of plastic garbage yearly (CPCB). Biodegradable plastics offer an alternative by potentially reducing long-term waste accumulation and associated hazards. However, in India, awareness, availability, and scientific validation of biodegradable plastics remain limited (ISSD). Many of the products marketed as biodegradable lack transparent performance data, particularly in India-relevant conditions, including dry heat and chemical exposure generally experienced during storage and disposal in landfills. This study aims to bridge this gap by analyzing the degradation rate of a certified biodegradable packaging material. Using industry-provided data and new experiments, the project evaluates the material's performance under controlled dry heat and chemical environments. Approved by the sponsoring company, the sample under investigation presents a chance to produce repeatable data that could guide consumer behaviour as well as policy decisions in the sustainable packaging market of India. The material is experimented by manipulating aging circumstances and observing physical, chemical, and visual degradation throughout time in order of experimental approach. Initial findings should support if the material can satisfy performance criteria under Indian market settings. Ultimately, the study contributes to the growing body of knowledge needed to support the responsible adoption of biodegradable plastics in India.***

Keywords: Biodegradable, Plastics, Pollution, Degradation Studies, Waste Management

1. Introduction

1.1 Plastic Packaging & Waste Management in India

India has seen a huge rise in plastic use over the past ten years, especially in the packaging industry. This has made it difficult to deal with post-consumer plastic waste, which usually ends up in landfills, bodies of water, or open dumps. According to a thorough review of India's plastic waste policies from 1992 to 2020, the country has had trouble enforcing consistent rules because its implementation systems are broken, its infrastructure is lacking, and its enforcement mechanisms are weak (Rafey et al., 2021). Even though the Plastic Waste Management Rules were updated in 2016 and 2021, they are still not always followed and find effects on the ground. A lot of plastic waste comes from packaging, and the disposal of it is still a problem for local governments. According to Akinola et al. (2014), integrated plastic waste management (IPWM) is one of the best and most environmentally friendly ways to deal with plastic waste. IPWM includes reducing, recycling, separating at the source, and recovering energy. Biodegradable plastics, which are becoming more popular, can still pollute the environment by making microplastics, especially if they aren't composted in the right way (Kedzierski et al., 2020). The informal recycling industry in India is very important for collecting and sorting trash, but it doesn't get any official help. Drzyzga., & Prieto (2018) say that community-driven biotechnology and waste reduction programs are very important. These systems work best when they are combined with grassroots involvement and decentralised ways to reuse and break down plastic.

To tackle the issues with traditional plastic and its disposal, researchers are looking into how biodegradable alternatives affect the real world in India because an increasing number of consumers are interested in them. For example, Flury & Narayan (2021) say that biodegradable plastics should only be used with clearly defined ways to get rid of them. Filiciotto & Rothenberg (2021) also say that biodegradable plastics may break down unevenly or release toxic by-products if they are not handled properly. Because synthetic polymers don't break down in nature, it's even more important to find and use more eco-friendly materials (Aminabhavi et. al., 1990). Recent advances in materials that break down naturally are promising. Dias et al. (2025) did a study that showed how to turn plant-based fibres like flax and cotton into biodegradable cellulose acetate using sulphuric acid. This gives us options other than petroleum-based plastics. Meanwhile, Nanda and Berruti (2021) talk about how biodegradable plastics could help a circular bioeconomy if production, use, and disposal are made easier across all industries. Polymer behaviour in certain conditions is a key factor in determining real sustainability. For example, a 2025 review found that the degradation of biodegradable plastics in soil depends on their chemical structure, the presence of microbes, and the humidity (Withana, et al., 2019).

The literature as a whole makes it clear that switching to biodegradable plastics alone is not a quick fix. How well these materials work depends a lot on how well the rules are followed, how well the city's infrastructure is set up, and how much people know about them. India needs to find all-around solutions that include regulatory reform, new ideas, education, and putting money into waste systems that are good for the environment.

1.2 Biodegradable Plastics in the Indian Context

As India's plastic waste problem gets worse, more people are looking into biodegradable alternatives as a way to reduce long-term damage to the environment. Policymakers and scientists are looking more urgently at biodegradable plastics as a way to help with the problem of traditional plastics piling up in landfills and bodies of water. This is especially true for packaging, agricultural films, and single-use items. But the Indian landscape makes it hard to adopt, use, and enforce policies, even though the potential is huge.

Biodegradable plastics are made to break down into water, carbon dioxide, and biomass through the action of microbes. However, how sustainable they will actually prove to be for the environment depends on things like temperature, humidity, the presence of microbes and their respective consortiums, as well as the availability of waste treatment facilities (Withana, et al., 2019). In India, where open dumping and uncontrolled landfilling are still common, these ideal conditions for degradation are not often met. Because of this, several products that are called biodegradable might break down only partially or turn into microplastics, especially in soil or water (Mostafa et al., 2018). Moreover, biodegradable plastics are not naturally sustainable unless they are used with clear systems for collecting, sorting and disposing them away. Nanda and Berruti (2021) stress that these materials need to be part of a circular bioeconomy, where their life cycle—from getting the raw materials to treating them after use—is carefully planned. This is especially important in India, where the recycling system is still very informal and there isn't much separation between biodegradable and non-biodegradable plastics.

The Government of India has begun to promote bioplastics through a number of policy statements and pilot projects that aim to change how people think about them and how they are used. The current rules, on the other hand, don't have clear rules for labelling, certification, and disposal, which can confuse customers and hurt environmental goals (Shah et al., 2023). For instance, a product that says "biodegradable" might still need to be composted in an industrial setting, which is not common in Indian cities or rural areas. Researchers have looked into biomass-based alternatives that use cellulose, starch, and natural fibres from a technological point of view. Dias et al. (2025) showed a promising way to turn flax and cotton into cellulose acetate using sulphuric acid. The results were materials that are both strong and biodegradable. Still, it would be hard to scale up these kinds of solutions in India because of high costs, short supply chains, and a lack of composting on an industrial scale. Dissanayake et al. (2024) backs up the idea that the type of polymer affects how bioplastics break down in Indian soil. For example, polylactic acid (PLA) and polybutylene adipate terephthalate (PBAT) break down more reliably in controlled composting than in natural soils, where changes in climate and the presence of different types of microbes make it harder for them to break down. Lastly, Yates & Barlow (2013) say that the key to using biodegradable plastics in a way that doesn't harm the environment is not just the material itself, but also how the system is set up. That includes teaching people about it, separating trash in cities, giving people incentives to build composting infrastructure, and strict certification to keep people from greenwashing. In short, biodegradable plastics are a good way to help cut down on plastic pollution in India, but they aren't the only way. India needs to make quick progress in a number of areas, such as product design, disposal conditions, regulatory oversight, and public involvement, in order to see real environmental benefits. A summary of currently available biodegradable plastics, either commercially accessible or under research or technical development have been discussed in Table 1.

Table 1: List of commercially and potentially significant biodegradable plastics with their technical attributes and market presence

Material Type	Composition & Source	Production Method	Cost Range	Degradation Rate & Environment	Mechanical Properties	Gas/Moisture Permeability	Toxicity	GHG Emissions	Markets/Use Cases	Sources
PLA (Polylactic Acid)	Corn starch, sugarcane (renewable biomass)	Polymerization of lactic acid	₹120–180/kg	Industrial composting: 90-180 days; Slow in soil and water	Tensile: 50–70 MPa, brittle, low impact resistance	Low oxygen permeability, low moisture barrier	Low toxicity; additives impact varies	CO_2 under composting; possible methane in landfill	Food packaging, cups, agricultural films; globally available	NatureWorks LLC, 2023; European Bioplastics, 2022
PBAT	Fossil-fuel derived but biodegradable aliphatic-aromatic copolyester	Copolymerization	₹160–220/kg	Industrial composting: 90 days; limited soil degradation	Tensile: 20–30 MPa, highly flexible	High gas and moisture permeability	Low acute toxicity; limited long-term data	CO_2 in composting, moderate GHG in landfill	Compostable bags, films; Europe, India adoption increasing	BASF Ecoflex TDS, 2023; European Bioplastics, 2022
PHA (Polyhydroxy-alkanoates)	Bacterial fermentation of sugars/oils	Microbial biosynthesis	₹400–600/kg	Biodegrades in soil, marine, compost: 60-180 days	Tensile: 30–40 MPa, moderate flexibility	Moderate gas permeability, high moisture sensitivity	Generally low toxicity, biodegradable residues	Low GHG in composting; aerobic preferred	Medical applications, premium packaging; niche markets	Danimer Scientific, 2023; European Bioplastics, 2022
Starch Blends	Starch (corn, potato) + PBAT/PLA	Blending, extrusion	₹80–150/kg	Soil degradation: 120-360 days; faster in compost	Low tensile (10–20 MPa), high flexibility	High moisture permeability	Degradation products generally safe	Anaerobic digestion may produce methane	Shopping bags, single-use cutlery; India	BIS IS/ISO 17088:2021; CPCB Report, 2023

									widespread use	
Cellulose Derivatives	Flax, cotton fibres (cellulose acetate)	Sulphuric acid acetylation	Not commercially scaled in India	Soil: 90-180 days; marine: variable	High rigidity; brittle without plasticizer	High moisture absorption	Low toxicity (natural cellulose basis)	Low GHG but lacks large-scale data	Packaging films; limited commercial products	ASTM D6868; UNEP, 2021
PBSeT (Polybutylene sebacate co-terephthalate)	Biobased sebacic acid, terephthalic acid	Copolymerization	₹200–300/kg	Compostable within 90 days; stable in soil	Good flexibility, moderate tensile strength	Moderate barrier properties	Limited data	Low GHG in composting	Early-stage commercial; EU focus	EU Bioplastics Database, 2022
Blended Bioplastics (Proprietary)	Mixed PLA, PBAT, starch, PCL	Extrusion & proprietary formulations	₹150–250/kg	Manufacturer claims composting in 60–180 days; field data varies	Customized properties	Varies widely based on blend	Unknown; not publicly reported	Unknown; varies	Packaging films, shopping bags; India imports & local production	Manufacturer specification, 2023

1.3 Recent Developments in Biodegradable Plastics

The characteristics, patterns of degradation, and real-world uses of biodegradable plastics have been the subject of numerous studies, patents, and commercial reports in recent years. These materials, which come from a variety of natural and artificial sources, are being increasingly marketed as substitutes for traditional plastics in consumer goods, packaging, and agriculture. However, a number of variables, such as the composition of the material, processing techniques, end-of-life management options, and environmental conditions, affect their performance characteristics and degradability in the real world. A survey of recent research shows that biodegradable plastics present both advantages and disadvantages. Key components from a compositional standpoint are cellulose derivatives, starch blends, polylactic acid (PLA), polybutylene adipate terephthalate (PBAT), and polyhydroxyalkanoates (PHA). Certain materials, like PLA and PBAT, can be composted in an industrial setting under controlled conditions, whereas PHA degrades better in natural settings but costs more (Dissanayake et al., 2021). These materials' mechanical qualities vary greatly; PLA has a high tensile strength but low flexibility, while PBAT and starch blends offer more flexibility at the expense of strength (Afsar et al., 2024). Likewise, gas permeability data shows that PLA has a low oxygen permeability, making it suitable for food packaging, while PHA and PBAT can allow for more moisture transfer, which may or may not be beneficial depending on the application (Nanda & Berruti, 2021). Another important factor is environmental performance. According to some studies, if biodegradable plastics are not properly composted in anaerobic landfill conditions, they may release greenhouse gases (GHG) like methane. Additionally, there are still a few toxicity studies available; some bioplastics show minimal toxicity when composted, but some additives may leak toxic substances if they are not properly prepared (Yadav & Nikalje 2024).

2. Aim of the Study

Biodegradable plastics offer a strong alternative because they are made up of materials that can decompose faster than normal plastics and produce relatively safer & simpler compounds under the same appropriate conditions, thereby reducing long-term pollution. However, in the Indian market, there remains a significant gap in awareness, availability, and research regarding biodegradable materials' actual performance under different environmental conditions. Many products claim biodegradability, but standardized data on their degradation rate, particularly under dry heat and chemical exposure, are lacking. This study aims to address this gap by analyzing the degradation of a commercially available biodegradable packaging material, biodegradable plastic, using data from a certified degradability report by applying various analytical techniques & under different degradation conditions, chemical and thermal. The commercial sample product, sponsored by an industry-leading company, offers a unique opportunity to contribute transparent, reproducible data to the field. The goal is to evaluate whether such materials can meet the demands of Indian consumers and policymakers seeking sustainable packaging solutions.

3. Methodology

3.1 Materials

A commercially available biodegradable packaging film under the brand name MOO2, as show in Figure 1, supported by Hi Tech International, India, a top packaging manufacturer, served as the test sample for this investigation.

Figure 1: Biodegradable Plastic Sample, MOO2

Before being tested, the samples were kept in a laboratory environment in sealed rolls. Different reagents utilized during testing are Sodium hydroxide (NaOH, analytical grade), Sulfuric acid (H_2SO_4, 0.01 N), Hydrochloric acid (HCl, 0.1 N), Nitric acid (HNO_3, trace metal grade for digestion), Buffer solutions for pH calibration, Calibration standards for total organic carbon and heavy metal analysis. These were procured from Sigma-Aldrich. Compost substrate components such carrots, onions, peppers, rice, soybeans, sawdust, and plotting soil were obtained from local markets.

3.2 Heavy Metal Analysis

Standardized methods were used to analyze the test samples' heavy metal content. Following pyrohydrolysis in compliance with EN 15408:2011, the amount of fluorine (F) was detected using either ion chromatography, Metrohm 930 Compact IC Flex or an ion-selective electrode, Thermo Scientific Orion Star™ ISE Metre. The acid digestion with nitric acid was carried out in a microwave digestion system, while the other metals such as lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr), were examined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Agilent 7900 ICP-MS in accordance with ISO 17294-2:2016.

3.3 Thickness Testing Method

A digital micrometer gauge, Mitutoyo Quickmike Series 293-IP-54 Absolute Digimatic Micrometer was used to measure the film thickness in accordance with EN 71-1:2014+A1:2018 Clause 8.25.1, which refers to ISO 4593:1993. Each test specimen was measured at ten randomly selected locations. The results were recorded in micrometres and presented as mean ± standard deviation.

3.4 Biodegradation Testing

In accordance with ISO 14855-1:2012, which measures the carbon dioxide (CO_2) evolved during composting as a stand-in for degradation, aerobic biodegradation was assessed under controlled composting conditions. The protocol was modified in accordance with AS 5810:2010 and NF T51-800:2015 to account for the ambient environmental conditions in India. A constant temperature of 25 ± 5°C was used for all tests. The reference material used for the testing was microcrystalline cellulose. The vessel used for biodegradation test was procured from Pyrex Co.Ltd and were high pressure conical flask with volumes of 3000 ml. The amount of carbon dioxide evolved was determined by weighing the carbon dioxide absorbing system. The amount of carbon dioxide was calculated via the difference in the weight of the carbon dioxide absorbing trap in the beginning and in the end of the test. The validity criteria followed were (a) the degree of biodegradation of reference material after 90 days had to be more than 70%; (b) the difference between percentage biodegradation of reference material in the different vessels at the end of test had to be less than 20% and (c) the average CO2 production in the blank vessels after 10 days had to be within the range 10 mg to 50 mg CO2 /g volatile solids (Leejarkpai et. al., 2011; Saha et. al., 2019).

Choosing an appropriate compost and assessing its 10-day activity was the first step in the biodegradation testing procedure. Next, the compost's overall dry-solids and volatile-solids contents were ascertained. After making a mixture of compost and deionized water, the pH level was determined. The experiment was set up with nine vessels: three holding the reference material (R1, R2, R3), three holding the test material (T1, T2, T3), and three serving as blanks (B1, B2, B3). These vessels were kept in an oven with water-saturated air and kept at 25 ± 5 °C. The oxygen content of the exhaust air from the composting vessels was tracked during the test. A weekly check was carried out to note the compost pH, the amount of the carbon dioxide produced, while maintaining the moisture content of the test mixture at 50%.

3.4.1 Total Organic Carbon (TOC)

Using a Shimadzu TOC-L Series analyzer, the TOC content of the test and reference materials was determined by catalytic combustion at 900°C. In order to normalize the evolution of CO_2 and calculate the percentage of biodegradation, the results were expressed as a percentage of the dry mass (Hong et. al., 2021).

3.4.2 Inoculum Characterization

Inoculum was sourced from pre-composted municipal organic waste obtained from a certified composting facility. It was sieved to <10 mm and characterized for the following: moisture content, 54.4%; C:N ratio, 30:1; pH, 7.32; and volatile solids, 65.6% of dry mass. These parameters conform to the requirements outlined in ISO 14855-1:2012 for promoting optimal microbial activity during aerobic biodegradation testing (Tchobanoglous et al., 2002; Adhikari et al., 2008).

3.4.3 CO_2 Evolution Monitoring

Alkali traps with 0.5 N NaOH solution were used in sealed composting vessels to measure CO_2 emissions. In accordance with ISO 14855-1 protocols, the CO_2 content was measured by periodic titration using 0.25 N HCl. Every day, the compost's temperature and oxygen content were checked. Reliability was ensured by using duplicate experimental setups for both test and reference samples.

3.4.4 Dry Mass Post-Composting

Following 180 days of composting, the leftover solids were filtered, cleaned, and oven-dried for 24 hours at 105°C before being weighed to determine the final dry mass. To ascertain disintegration, the mass loss was computed and examined in conjunction with visual and sieve-based evaluations.

3.5 pH Testing

The pH value of the compost was measured by diluting the compost with deionised water in the ratio of 1:5 10g of dry soil was taken in a bottle and 50 mL deionised water was added in. This was followed by mechanical shaking for 1 hour at 50 rpm. The pH meter, ANALAB pHcal5+, was calibrated using the standards, before the measurement of the compost samples. The measuring electrode was washed with deionised water between measurements (Costello & Sullivan, 2014).

3.6 Disintegration and Composting Method:

The method utilized in this is the ISO 16929:2021 with modifications. The test environment was maintained at an ambient temperature of 25 ± 5°C. The general test duration was kept at 180 days, with certain exceptions. The control or blank compost was prepared using a mixture of 7.0kg soil, 1.2kg onions, 1.2kg carrots, 1.2kg pepper, 1.5kg sawdust, 1.9kg rice and 1.0kg soybeans, whereby the mass considered for rice and soybeans is wet mass after soaking the rice and the soybeans in water for 12 hours. The total weight of the wet mass of the blank compost was 15 kg. The conditions at the start of the experiment of the blank post were recorded. The water content was determined to be at 54.4%, the C-N ratio was 30, pH was 7.32 and the volatile solids was 65.6% of total dry mass. The experimental compost was prepared by adding the MOO2 pieces in 10cm X 10cm sizes to the blank compost. Incubation ovens were then used to test the disintegration process, where the temperature was monitored daily, with periodic turning of the compost and measurement of oxygen concentration by Cy-C12 Oxygen Analyzer [BENEMED] from the exhaust gas directly. The tests were conducted in duplicates for both control and experimental setups. Following the test phase, the compost was sieved to determine the dry mass of the test material that did not degrade and the Rottegrad of the compost was determined. The Rottegrad is a parameter for determining the maturity of the compost obtained after the test on disintegration. After 180 days the final compost is placed in Dewar vessels for 72 hours. The highest temperature during these 72 hours is used for comparing with the limits for the different Rottegrads. The different parameters measured for the samples post-disintegration were total dry solids, volatile solids, pH, Phosphorus, Nitrite (N), electrical conductivity, Total nitrogen as N, Nitrate as N, Ammonium nitrogen as N, Potassium, Magnesium, Volumetric density, Total organic carbon (Afsar et.al., 2025; Veeken et. al., 2003).

3.7 Plant Test

The methods utilized in this are the EN 13432: 2000 Annex E and OECD 208: 2006 with modifications. In this test, corn, *Zea mays* and soybean, *Glycine max (G. soja)* are used. They are grown in 10L polypropylene pots. The control soil constitutes of mixture of commercial potting soil as substrate (peat soil) and siliceous sand whose parameters were tested and found to be soil particle distribution: < 6mm; Total organic carbon: 32.0%; Volatile solids content: 57.6%; Total dry solids: 59.6%; pH value: 7.12. The experimental soil containing the composted MOO2 utilized composts < 10mm fraction and consisted of sample compost and blank compost obtained after 12 weeks of composting and sieving with 10mm sieve according to ISO 16929: 2021. 24 pots were prepared and filled with mixtures of the reference substrate with 25% or 50% (w/w) of blank compost or sample compost, as per Table 2. The total soil in each pot is 1400.0g, and peat soil is mixed with siliceous sand in a ratio of 1:1(w/w) to prepare the reference substrate. Moreover, 3 parallels were set for each mix ratio, and the pot numbers are listed in Table 3. 100 seeds of soybean or corn were evenly placed in each pot and water was added. After watering, the pots were set in a greenhouse where they stayed in the dark during the germination period. The plants were watered daily, and no additional fertilization was used. The temperature was maintained at 22°C ± 10°C, while the relative humidity was controlled to remain at 70% ± 25%. The photoperiod observed was 16 hours/day. The light luminance measured at the top of the canopy was kept at 25900 lx ± 3700 lx (350 ± 50 µE/ m2/s) but no less than 14800 lx (200 µE/ m2/s). Post-germination of 50% of the seeds in the pots with a mixture of blank compost, the plant growth test was kept running for 14 ~ 21 days.

Table 2: Weight Distribution of each Plant Pot

Mix Ratio	Weight (g/pot)		
	Blank/ Sample Compost	Reference Substrate	Total
25 %	350	1050	1400
50 %	700	700	1400

Table 3: Plant Pot Numbers & Experimental Distribution

Plant	Mix Ratio (%)	Pot Number	
		Blank Compost	Sample Compost
Soybean	25	Parallel 1-3	Parallel 1-3
	50	Parallel 1-3	Parallel 1-3
Corn	25	Parallel 1-3	Parallel 1-3
	50	Parallel 1-3	Parallel 1-3

4. Results

4.1 Heavy Metals Testing

The heavy metal analysis was carried out for our sample, MOO2 and all the tested elements were reported to be below the threshold limit, except for copper which as noted in Table 4 was higher than the threshold limit at 8 mg/kg. The tested values have been determined to be well below the limits prescribed by EN 13432, US, Canada, France (NF T51-800), China, and Japan.

Table 4: Results of Heavy Metal Analysis

Test Parameter	Reporting Limit (RL) (mg/kg)	Test Result
Zn	5	<RL
Cu	5	8
Ni	5	<RL
Cd	0.25	<RL
Pb	5	<RL
Hg	0.2	<RL
Cr	5	<RL
Mo	0.25	<RL
Se	0.25	<RL
As	0.25	<RL
F	50	<RL
Co	3	<RL

4.2 Thickness of the Material

To test the thickness of the material, ten trial runs were made in triplicate, and the average was found to range between 0.0007 and 0.0015mm. The data has been represented in Table 5.

Table 6: Thickness Trial Measurements

Trial	T001 (mm)	T002 (mm)	T003 (mm)
1	0.014	0.015	0.024
2	0.013	0.015	0.023
3	0.014	0.015	0.025
4	0.015	0.016	0.024
5	0.014	0.015	0.026
6	0.014	0.015	0.026
7	0.016	0.016	0.026
8	0.014	0.016	0.027
9	0.013	0.017	0.028
10	0.015	0.015	0.025

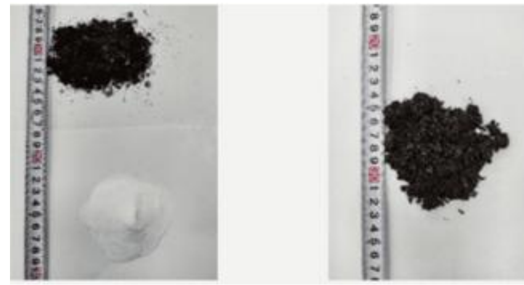
4.3 Controlled Aerobic Biodegradation Test

The controlled aerobic testing of bioplastics are important to measure their biodegradability under pre-determined conditions, such that they are broken down into simpler and non-toxic compounds, thereby minimizing environmental impact. Testing of the samples in this manner ensures that the standards for compostability can be ascertained (Witt et. al., 2001). The results have been summarized in Table 6, while Figure 2 depicts the visual representation of compost (a) without any material, (b) with reference material, microcrystalline cellulose and (c) with testing material, MOO2, before and after testing.

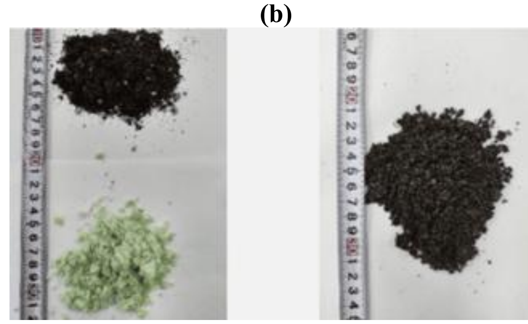
Table 6: Overall Summary of Controlled Aerobic Biodegradation Test

Test Parameters	MOO2	Microcrystalline Cellulose
90 days Biodegradation Rate (%)	46.02	74.15
Overall Biodegradation Rate (%)	92.70	99.80
Test Duration (days)	230	230
Observation	No deviation from normal	No deviation from normal

(a)



(b)



(c)

Figure 6: Visual representation of compost (a) without any material, (b) with reference material, microcrystalline cellulose and (c) with testing material, MOO2 where each image on the left depicts compost with/without reference/test material before testing and each image on the right depicts after testing

The inoculum, a commercial compost termed Peilei chosen for the compost testing was obtained from pre-composted municipal organic waste that was procured from a certified composting facility. The properties of the inoculum has been reported in Table 7.

Table 7: Properties of the Inoculum Compost

Properties	Description
Age	2 months
Storage condition	dry and room temperature
Handling	sieved through 10 mm
Total dry solids (%)	51.3
Moisture content (%)	48.7
Volatile solids (%)	45.7
Ash (%)	54.3
Compost Activity Test (mg CO_2 /g volatile solid)	30.8
Total organic carbon (%)	14.5
Total nitrogen content (g/kg)	8.63
Carbon/ Nitrogen ratio	16.8
pH of suspension	7.12

4.3.1 CO_2 Evolution Curve

The composting material was checked every day, and its activity was measured on a day-to-day basis for the first 10 days. During this time, the amount of CO_2 released was noted, and the average of 30.8 mg of CO_2 per gram of volatile solids was reported or observed. Each vessel contained 1.2 kg of composting material. The CO_2 evolution curve from the showed a clear, consistent increase in CO_2 levels from the test material, peaking near 85 days. The curves in Figure 7 displayed sigmoidal trends, which are indicative of aerobic composting conditions and microbial activity. After about 110 days, the CO_2 release stabilized, suggesting that most of the degradation process was over.

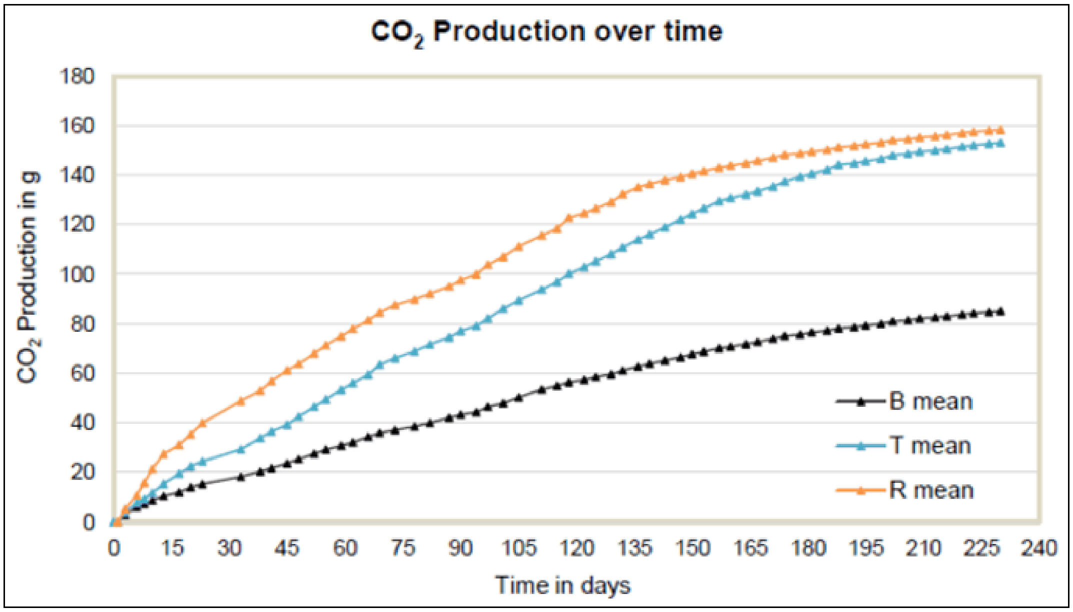


Figure 7: Mean Carbon Dioxide Production over 230 days in Blank Compost (B), Compost with Reference Material (R) and Compost with Test Material (T)

4.3.2 Total Amount of Organic Carbon & Compost in Vessels

The contents of organic carbon in test and reference material (microcrystalline cellulose) were determined. Results were used for calculation of amount of test material necessary to have an amount of 20g organic carbon in each vessel. The amount of required organic carbon for each vessel in case of the reference material was found to be 47.8 g, and it was 73.3g of CO_2 if the microorganisms had a biodegradation rate of 100%. The various properties of the reference material and the test material are compared in the Table 8 and the amount of the materials, both reference and test are reported in Table 9.

Table 8: Properties of the reference material and the test material

Parameter	Microcrystalline Cellulose	MOO2
Total organic carbon (TOC %)	41.8	58.4
Amount of TOC in test vessel (g)	20	20
Theoretical amount of evolved carbon dioxide (g)	73.3	73.3
Volatile solids (%)	100	93.1
Requirement for volatile solids (%)	_	>50
Total dry solids (%)	95.7	99.9
Moisture content (%)	4.3	0.1

Table 9: Material Distribution in the different Composts

	Compost		Material	
	Weight (g)	Total Dry Solids (g)	Weight (g)	Total Dry Solids (g)
Blank	1200	615.6	None	None
Reference	1200	615.6	47.8	45.7
Test	1200	615.6	34.2	34.2

4.3.3 pH Value

The pH testing was carried out for nearly 230 days, and the pH of the compost was determined by diluting the compost with distilled water in the ratio 1:5 and measuring the value with an electrical pH meter.

Table 10: pH values

Day	B_mean	R_mean	T_mean
1	7.09	7.11	7.1
8	7.16	7.16	7.15
17	7.18	7.15	7.17
23	7.15	7.14	7.22
38	7.13	7.16	7.15
45	7.24	7.16	7.12
52	7.11	7.16	7.15
59	7.26	7.21	7.1
66	7.12	7.13	7.1
73	7.16	7.15	7.16
87	7.17	7.18	7.15
94	7.15	7.13	7.18
101	7.17	7.15	7.17
115	7.17	7.17	7.1
122	7.16	7.14	7.15
129	7.14	7.2	7.15
136	7.2	7.12	7.19
143	7.17	7.18	7.13
150	7.16	7.15	7.16
157	7.13	7.13	7.15
164	7.18	7.15	7.13
171	7.16	7.2	7.15
178	7.13	7.16	7.12
185	7.17	7.08	7.16
192	7.14	7.15	7.2
199	7.12	7.16	7.16

206	7.12	7.14	7.13
213	7.12	7.15	7.11
220	7.16	7.13	7.13
227	7.12	7.18	7.15
230	7.11	7.13	7.17

4.3.4 Biodegradation Curve

The MOO2 test material achieved 91.8% biodegradation after 180 days, according to the biodegradation curve that was computed from the cumulative CO_2 evolved. The effectiveness and microbial activity of the composting system were confirmed by the reference cellulose material used for calibration, which reached 96.3%. The requirement of ≥ 90% biodegradation within 180 days was fully met by the test results.

Controlled Aerobic Biodegradation Test Data of Test Material			
Day	B_mean_CO2	T_mean_CO2	T_mean_D
1	0	0	0
3	3.03	3.98	1.3
6	2.92	3.77	1.16
8	1.33	1.55	0.31
10	1.39	2.46	1.46
13	1.84	3.59	2.38
17	1.43	4.12	3.67
20	2	2.94	1.28
23	1.37	2.01	0.87
33	2.92	5.01	2.85
38	2.14	4.46	3.16
41	1.41	2.68	1.73
45	1.88	2.67	1.09
48	1.67	3.27	2.19
52	2.27	4.07	2.46
55	1.62	2.89	1.74
59	1.58	3.89	3.15
62	1.26	2.15	1.99
66	2.36	3.44	1.68
69	1.73	4.04	3.12
73	1.49	2.36	1.8
78	1.4	2.76	1.85
82	1.35	2.25	1.91
87	2.3	2.63	1.1
90	1.63	2.26	1.17
94	1.21	2.05	1.45
97	2.77	2.92	1.35
101	4.48	3.17	3.46
105	2.6	3.22	1.35
111	3.08	1.49	1.57
115	3.43	3.16	2.26
118	2.4	5.25	2.76
122	2.82	5.22	3.12
125	2.68	2.41	1.74
129	2.51	2.39	2.39
132	2.32	1.43	1.68
136	2.64	2.06	2
139	2.17	1.19	1.25
143	2.32	2.27	2.51
147	3.32	1.98	2.46
150	1.87	1.57	1.45
153	2.1	1.63	1.63
157	2.71	1.83	1.86
160	1.62	1.31	0.99
164	1.38	0.96	0.96
167	1.27	0.74	0.77
171	1.26	0.25	0.17
174	1.25	1.84	1.42
178	1.15	2.14	1.8

Controlled Aerobic Biodegradation Test Data of Reference Material			
Day	Bmean_CO2	Rmean_CO2	Rmean_D
1	0	0	0
3	3.03	5.32	3.12
6	2.92	5.47	3.48
8	1.33	5.11	5.15
10	1.39	5.48	5.59
13	1.84	6.16	5.89
17	1.43	3.62	2.98
20	2	4.21	3.02
23	1.37	4.56	4.35
33	2.92	8.96	8.24
38	2.14	4.16	2.75
41	1.41	3.77	3.21
45	1.88	4.45	3.51
48	1.67	2.9	1.12
52	2.27	3.97	2.67
55	1.62	2.31	2.34
59	1.58	2.58	2.74
62	1.26	3.03	2.41
66	2.2	2.56	1.71
69	1.73	3.02	2
73	1.2	2.76	2.49
78	1.4	2.21	1.1
82	1.35	2.34	1.35
87	2.08	2.94	1.17
90	1.33	2.6	1.74
94	1.01	2.32	1.8
97	2.17	3.86	2.37
101	1.44	3.15	2.33
105	3.01	4.06	2.31
111	3.23	4.25	1.66
115	1.51	2.86	1.89
118	1.33	4.35	4.12
122	0.96	1.77	1.42
125	1.17	1.94	1
129	1.08	2.58	2.05
132	1.48	3.14	2.26
136	1.68	2.88	1.64
139	1.42	1.32	0.16
143	1.21	1.35	0.05
147	1.32	1.35	0.05
150	1.23	1.26	0.04
153	1.07	1.13	0.08
157	1.38	1.39	0.02
160	0.62	0.8	0.23
164	1	0.99	0.02
167	0.86	0.88	0.03
171	1.28	1.2	-0.02
174	1.21	1.19	0.02
178	0.57	0.59	0.02
181	0.75	0.73	-0.03
185	0.72	0.7	-0.01
188	0.93	1.02	0.01
192	0.45	0.57	0.16
195	0.69	0.66	-0.04

199	0.69	0.66	0
202	0.9	0.87	0.74
206	0.51	0.58	0.09
209	0.66	0.6	0.15
213	0.49	0.52	0.11
216	0.43	0.46	0.05
220	0.81	0.82	0.16
223	0.44	0.48	0.23
227	0.47	0.45	0.03
230	0.44	0.45	0.02

4.4 Disintegration Testing during Composting

4.4.1 Amount of Test Material and Biowaste in Ovens before Disintegration

Prior to conducting the disintegration test, the biowaste and test material weighed as reported in Table 11.

Table 11: Weight of Biowaste and Test material

	Biowaste Wet mass (kg)	Test Material Wet mass in final form (g) MOO2-1	Test Material Wet mass in fine form (g) MOO2-2
Blank 1	15	None	None
Blank 2	15	None	None
Sample 1	15	157.5	1356.3
Sample 2	15	157	1355.2

4.4.2 Amount of Test Material after the Process of Disintegration

Following the disintegration testing, the final compost was sieved through a 2mm sieve, the remainder MOO2 samples were washed and dried. The material recovered was less than 10% of the sample amount placed in the biowaste at the beginning of the test. Hence the physical breakdown during the composting process was considered to be a successful one as can be seen from Table 12.

Table 12: Amount of Test Material after the Process of Disintegration in MOO2 samples

Parameter	MOO2-1	MOO2-2
Total dry mass of the sample used for the test (g)	157.3	156.3
Total dry mass of sample (> 2mm-fraction) after the test (g)	0	0
Degree of disintegration (%)	95	94

The wet mass of compost after the disintegration process was reweighed and reported as Table 13.

Table 13: Wet mass of compost after the disintegration process

Parameter (kg)	Values
Wet mass of the compost (Blank 1)	9.3
Wet mass of the compost (Blank 2)	8.5
Wet mass of the compost (Sample 1)	9.2
Wet mass of the compost (Sample 2)	10.7

4.4.3 Parameters of the Compost Achieved after Disintegration by Analysing the <10mm Fraction

The MOO2 samples recovered after passing the composted soil through the 10mm sieve were tested against various parameters and are reported in Table 14.

Table 14: Properties of Blank and MOO2 samples post-composting

Parameter	Blank 1	Blank 2	Sample 1	Sample 2
Total dry solids (%)	97.5	97.2	97.6	97.9
Volatile solids (%)	41.2	44.1	38.8	35.7
pH	7.22	7.22	7.19	7.03
Phosphorus (mg/kg)	4310	4490	4250	4410
Nitrite as N (mg/kg)	5.15	0.75	< RL	10.3
Electrical conductivity (μS/cm)	517	543	510	654
Total nitrogen as N (g/kg)	11.1	11.1	10.7	10.9
Nitrate as N (mg/kg)	229	225	27	33.5
Ammonium nitrogen as N (mg/kg)	14.4	15	31.6	29.6
Potassium (mg/kg)	19000	20100	19000	19500
Magnesium (mg/kg)	5430	5770	5940	6120
Volumetric density (Kg/L)	0.81	0.85	0.78	0.82
Total organic carbon (%)	31.6	33.1	33.2	32.7

4.4.4 Rottegrad of the Compost Achieved after Disintegration

The Rottegrad is a parameter for determining the maturity of the compost obtained after the test on disintegration. After 180 days the final compost was placed in Dewar vessels for 72 hours. The highest temperature during these 72 hours has been used for comparing with the limits for the different Rottegrads (Table 15). As mature compost did not undergo a significant self-heating process anymore, the temperature was reported below 30°C in Table 15. The changes in the compost can also be noted in the images reported in Figure 8 (Blank) and Figure 9 (Test Sample), as the soil and the composting mixtures proceeded to get darker with time, indicating the breakdown of the substances.

Table 15: Rottegrad Temperature & Grade Reference

Maximum Temperature	> 60°C	50.1°C to 60°C	40.1°C to 50°C	30.1°C to 40°C	≤ 30°C
Rottegrad	I	II	III	IV	V

Table 16: Rottegrad for Blank & MOO2 Compost

Parameter	Temperature after 72 h (°C)	Rottegrad
Blank 1	27.8	V
Blank 2	27.4	V
Sample 1	26.2	V
Sample 2	26.5	V

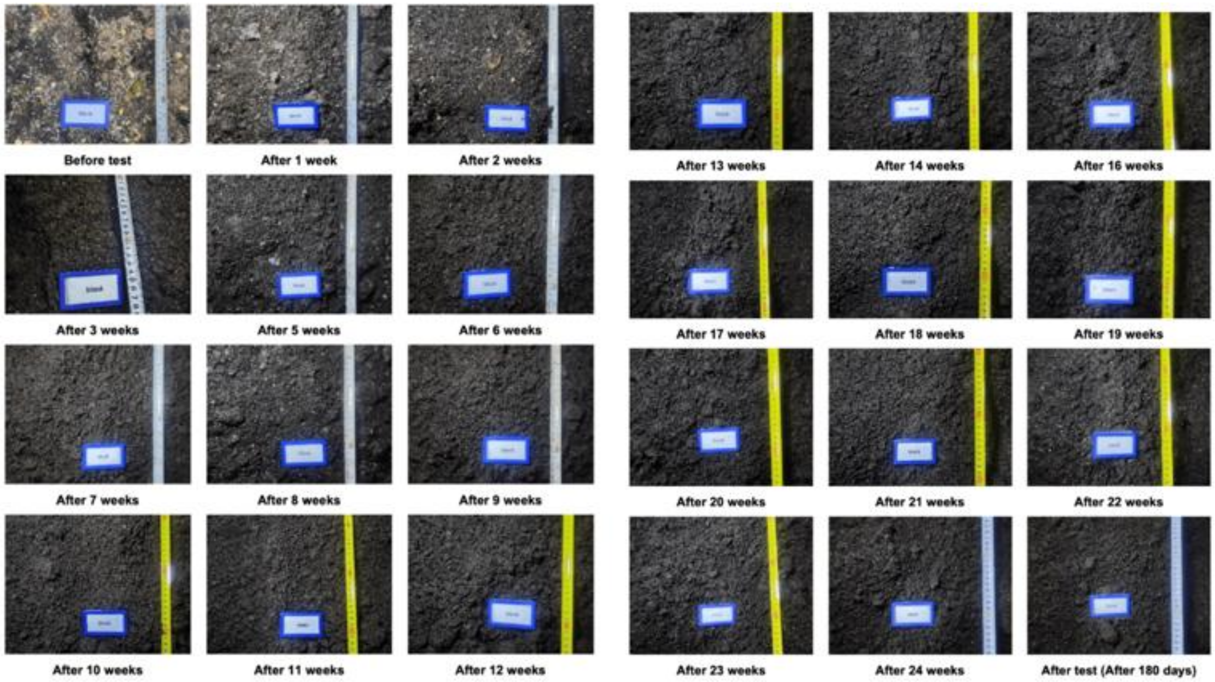


Figure 8: Change in the Blank Compost with Time

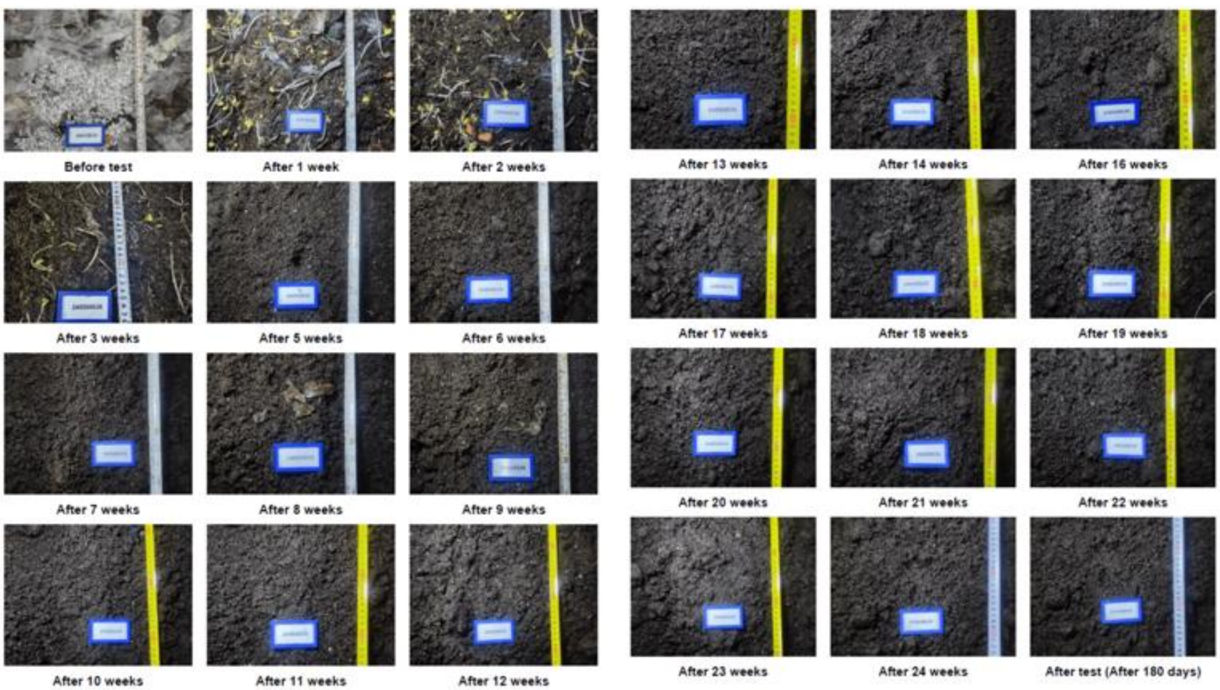


Figure 9: Change in the Test Sample Compost with Time

Variation in the temperature of the compost, the concentration of oxygen in the exhaust gas during the 180 days of testing as well as the changes in pH have been graphically represented in the figures 10, 11, and 12. The temperature was persistently found to be within the range of 25±5 °C. Moreover, that aerobic conditions were maintained, was proven by the concentration of the oxygen in the exhaust gas that were observed to be always greater than 10%. The pH-value remained between 6 to 9 during the testing period.

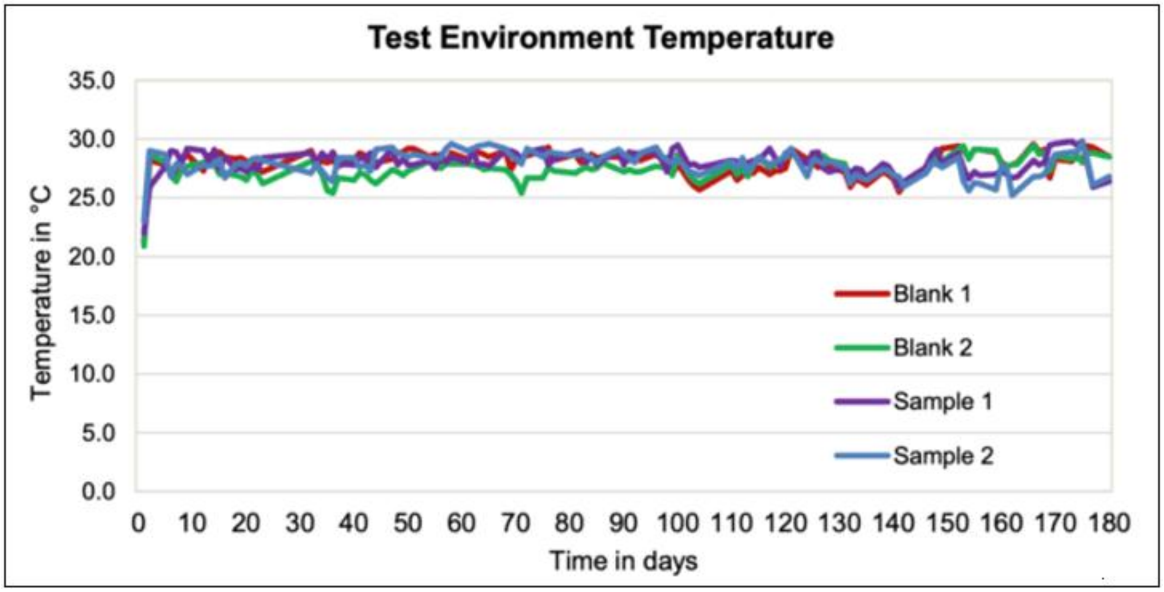


Figure 10: Variation in Test Environment Temperature during Composting

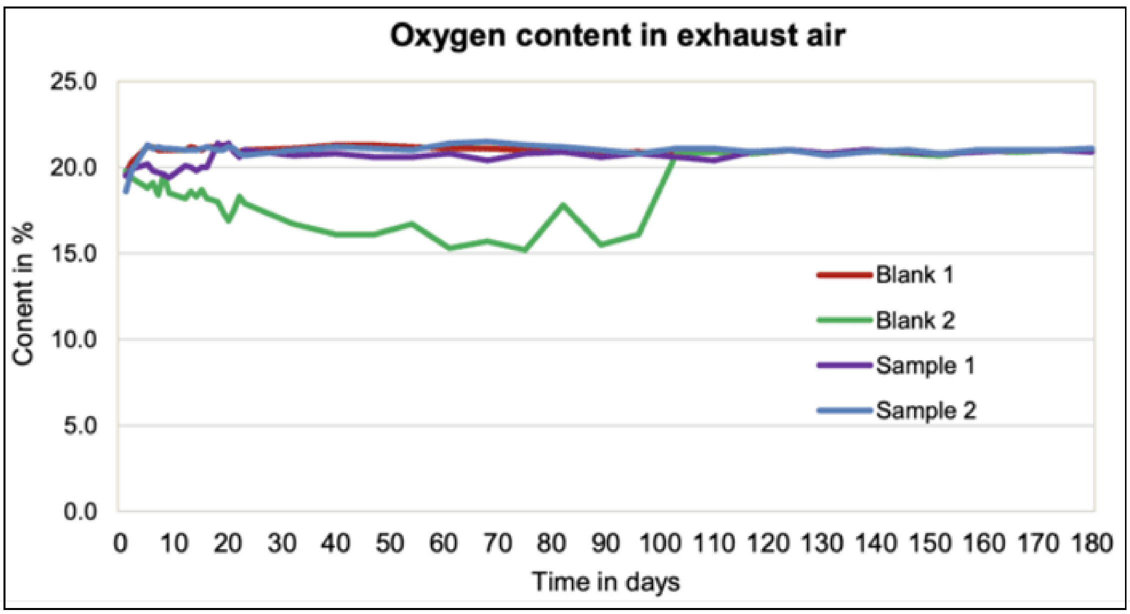


Figure 11: Variation in Test Environment Oxygen Content during Composting

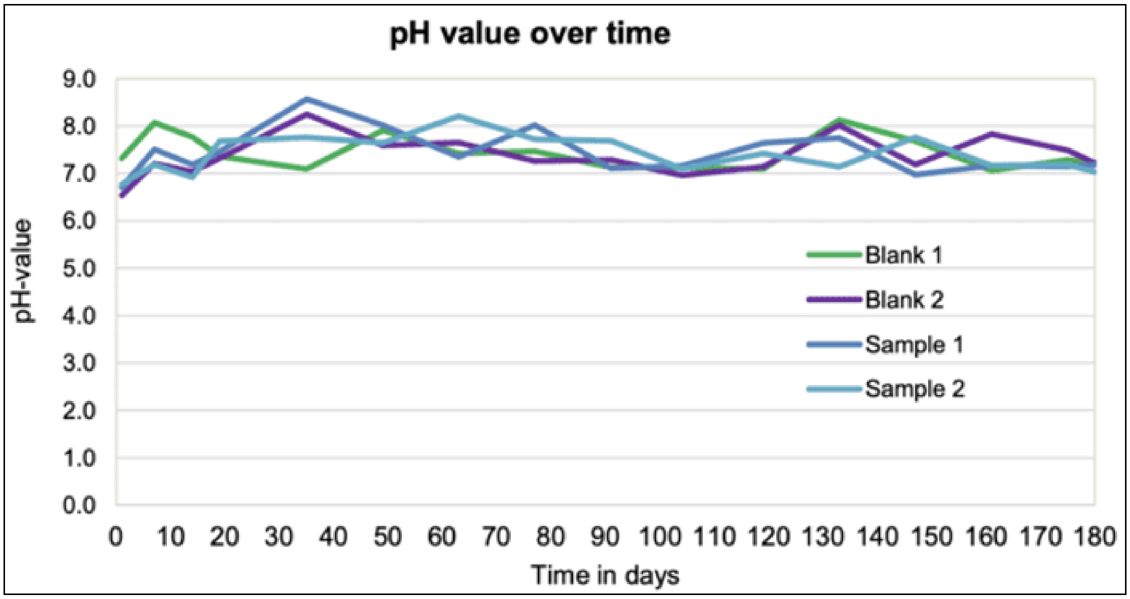


Figure 12: Variation in Test Environment pH during Composting

4.5 Plant Test

4.5.1 Summary

The plant test with the composted soil containing MOO2 samples was conducted for about 14 days as summarized in Table 16 and seen in Figs 13 (a) and (b) . Some conditions were maintained while undertaking this method - the seedling germination had to be about 70% and the conditions of the said seedlings were noted such that there were no signs of phytotoxic effects (e.g. chlorosis, necrosis, wilting, leaf and stem deformations) and the plants exhibited only normal variation in growth and morphology for that particular species. Moreover, the mean survival of emerged control seedlings had to be at least 90% for the duration of the study. Additionally, the environmental conditions for a particular species were kept identical and growing media contained the same amount of soil matrix, support media, or substrate from the same source.

Table 16: Summary of Germinating Plants in the 25% and 50% mix compost

Parameters	Plant	Mix ratio 25%	Mix ratio 50%	Requirement	Conclusion
Mean Germination Rate (%)	Soybean	98.6	99.6	≥ 90	Pass
Mean Germination Rate (%)	Corn	99.3	99.3	≥ 90	Pass
Mean Dry Biomass (%)	Soybean	98.7	98.9	≥ 90	Pass
Mean Dry Biomass (%)	Corn	98.1	99.7	≥ 90	Pass
Mean Wet Biomass (%)	Soybean	99	99.5	≥ 90	Pass
Mean Wet Biomass (%)	Corn	98	98.1	≥ 90	Pass

(a) Corn

Blank compost Sample compost
Corn growth, after test
25% Mix on the top, 50% Mix on the bottom

(b) Soybean

Blank compost Sample compost
Soybean growth, during test
25% Mix on the top, 50% Mix on the bottom

Blank compost Sample compost
Soybean growth, after test
25% Mix on the top, 50% Mix on the bottom

Figure 13: Germinating Plants in the 25% and 50% mix compost

4.5.2 Germination Rate

For the stage of germination, the pots were placed in the green room. It was observed that over 50% seeds from each pot had emerged within 4 days from the start of the experiment, the results of which have been summarized in Table 17 (a) and (b).

Table 17: Germination Rate of the Corn and Soyabean Plants in the Compost Pots

(a) Soybean

Mix ratio	Test No.	Germination of Soybean (Blank compost)	Germination of Soybean (Sample compost)	Germination Rate (%) sample compost as percentage of blank compost	Mean Germination Rate (%)
25%	Parallel 1	93	92	98.9	98.6
25%	Parallel 2	92	92	100	98.6
25%	Parallel 3	94	91	96.8	98.6
50%	Parallel 1	91	91	100	99.6
50%	Parallel 2	92	92	100	99.6
50%	Parallel 3	92	91	98.9	99.6

(b) Corn

Mix ratio	Test No.	Germination of Corn (Blank compost)	Germination of Corn (Sample compost)	Germination Rate (%) sample compost as percentage of blank compost	Mean Germination Rate (%)
25%	Parallel 1	92	91	98.9	99.3
25%	Parallel 2	91	92	101.1	99.3
25%	Parallel 3	93	91	97.8	99.3
50%	Parallel 1	93	92	98.9	99.3
50%	Parallel 2	92	91	98.9	99.3
50%	Parallel 3	91	91	100	99.3

4.5.3 Dry Biomass of the Plants

The plants were allowed to germinate for 14 days and then harvested from above their roots. The study then further explored the dry mass of the harvested plants as well by drying them at 60°C for 12 hours to further ascertain any difference between the blank and test pot-grown plants. The findings have been reported in Tables 18 (a) and (b).

Table 18: Dry Biomass of the harvested plants

(a) Soybean

Mix ratio	Test No.	Total Dry Biomass of Soybean (Blank compost)	Total Dry Biomass of Soybean (Sample compost)	Dry Biomass of Soybean (Blank compost)	Dry Biomass of Soybean (Sample compost)	Dry Biomass / (%) Sample compost as percentage of blank compost	Mean Dry Biomass (%)
25%	Parallel 1	20.3	19.6	0.221	0.218	98.6	98.7
25%	Parallel 2	20.1	19.2	0.221	0.211	95.5	98.7
25%	Parallel 3	19.8	19.9	0.215	0.219	101.9	98.7
50%	Parallel 1	19.2	19.5	0.213	0.217	101.9	98.9
50%	Parallel 2	20.3	19.8	0.223	0.218	97.8	98.9
50%	Parallel 3	20.8	19.7	0.226	0.219	96.9	98.9

(b) Corn

Mix ratio	Test No.	Total Dry Biomass of Corn (Blank compost)	Total Dry Biomass of Corn (Sample compost)	Dry Biomass of Corn (Blank compost)	Dry Biomass of Corn / plant (Sample compost)	Dry Biomass t (%) Sample compost as percentage of blank compost	Mean Dry Biomass (%)
25%	Parallel 1	10.5	10.7	0.117	0.119	101.7	98.1
25%	Parallel 2	10.7	10.3	0.119	0.114	95.8	98.1
25%	Parallel 3	11.1	10.4	0.121	0.117	96.7	98.1
50%	Parallel 1	10.5	10.4	0.114	0.114	100	99.7
50%	Parallel 2	10.6	10.5	0.118	0.118	100	99.7
50%	Parallel 3	10.3	10.2	0.114	0.113	99.1	99.7

4.5.4 Survival Rate of Plants

Almost all the plants survived until Day 14 with a mean survival rate of 98.5 % for corn and 98.9% for soyabean as reported in Table 19. The seedlings did not exhibit visible phytotoxic effects (e.g. chlorosis, necrosis, wilting, leaf and stem deformations) and the plants showed only normal variation in growth and morphology for soybean and corn.

Table 19: Survival Chart of the Corn and Soybean Plants

Plant	Mix Ratio	Test Number	Survival Numbers	Germination Numbers	Survival Rate (%)	Mean Survival Rate (%)
Soybean	25%	Parallel 1	92	93	98.9	98.6
Soybean	25%	Parallel 2	91	92	98.9	98.6
Soybean	25%	Parallel 3	92	94	97.9	98.6
Soybean	50%	Parallel 1	90	91	98.9	99.3
Soybean	50%	Parallel 2	91	92	98.9	99.3
Soybean	50%	Parallel 3	92	92	100	99.3
Corn	25%	Parallel 1	90	92	97.8	98.5
Corn	25%	Parallel 2	90	91	98.9	98.5
Corn	25%	Parallel 3	92	93	98.9	98.5
Corn	50%	Parallel 1	92	93	98.9	98.5
Corn	50%	Parallel 2	90	92	97.8	98.5
Corn	50%	Parallel 3	90	91	98.9	98.5

5. Conclusion

In this study, controlled aerobic composting, disintegration, and plant compatibility tests were used to assess the degradation performance of a certified biodegradable packaging film (MOO2) under simulated Indian storage and disposal conditions. The material met international compostability standards with a biodegradation rate of over 90% in 180 days, according to the results. With less than 10% of the material left over after composting, the disintegration tests verified that physical breakdown was successful. Furthermore, germination, biomass, and survival rates for corn and soybean consistently surpassed 98% across compost mix ratios in the plant growth tests, indicating no phytotoxic effects.

With the exception of a slightly higher copper content that was still well below dangerous limits, heavy metal analysis verified that the material met regulatory safety thresholds. Throughout the composting process, the temperature, pH, and oxygen levels all stayed within ideal ranges, demonstrating aerobic conditions and steady microbial activity.

All things considered, these results show that MOO2 has a great chance of being used sustainably in the Indian market—as long as it is disposed of in composting sites that are appropriately maintained. Effectiveness in the real world, however, will rely on the availability of industrial composting infrastructure, appropriate waste segregation, and unambiguous consumer guidance. Even certified biodegradable plastics run the risk of incomplete degradation and possible microplastic formation in the absence of these systems. Therefore, although materials such as MOO2 can contribute to India's efforts to combat plastic pollution, their full environmental benefits will only be achieved through public education, strong policy enforcement, and integrated waste management systems.

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