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Impact of Fibre Furnish, Biopolymer Surface Sizing, and Nano-materials on the Biodegradability behaviour of Paper


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Abstract: *Paper-based materials are increasingly being explored as sustainable alternatives to petroleum based material in packaging applications because of their renewable, recyclable, and biodegradable nature. However, packaging paper often requires surface modification to enhance its functional and barrier properties. Such modifications can be achieved through techniques including surface sizing, coating, lamination, metallization, and pigmentation etc. To further improve the strength and barrier performance of paper, nano-materials are frequently incorporated along with biopolymers. Among various surface treatment approaches, biopolymer based surface sizing are gaining significant attention due to their environmentally friendly characteristics. Depending on their composition, biopolymers may either inhibit or promote microbial activity, thereby influencing the biodegradation behaviour of paper.*

The present study investigates the effect of different fibre furnishes and biopolymer based surface sizing, with and without nano-materials (micro/nano cellulose), on the biodegradability of paper under soil burial conditions. Two fibre furnishes, wood pulp and recycled pulp i.e. old corrugated containers (OCC) were selected for the study. Hand-sheets prepared from each furnish were subjected to soil biodegradation testing to evaluate the influence of virgin and recycled fibres on degradation behaviour. Biodegradation was assessed through weight loss measurements and visual observation of physical changes during soil exposure.

To examine the role of surface modification, four different surface sizing systems were investigated, antimicrobial biopolymer based surface sizing with and without nanomaterial, and pro-microbial biopolymer based surface sizing with and without nanomaterial. The biodegradation behaviour of coated and uncoated hand-sheets was comparatively analysed under identical soil burial conditions.

Among the different fibre furnishes, OCC based hand-sheets degraded earlier than wood based hand-sheets under similar biodegradation conditions. This behaviour may be attributed to the structural and compositional characteristics of OCC fibres such as shorter fibre length and more fines, which facilitate faster fibre degradation.

The degradation behaviour of hand-sheets prepared from different fibre furnishes and surface sized with antimicrobial or pro-microbial biopolymers, with and without nanomaterial incorporation, was comparatively evaluated against non-surface-sized hand-sheets under identical soil burial conditions.

Hand-sheets treated with antimicrobial biopolymer surface sizing exhibited the slowest rate of degradation, whereas that surface sized with pro-microbial biopolymer showed comparatively faster degradation due to enhanced microbial activity and interaction. Furthermore, hand-sheets surface sized solely with antimicrobial or pro-microbial biopolymers degraded more rapidly than those containing biopolymer with nanomaterial combinations, indicating that the incorporation of nano-materials improved resistance to biodegradation.

The study demonstrates that both fibre furnishes and surface sizing composition significantly influences the biodegradation behaviour of paper based packaging materials. The findings provide valuable insight for the development of sustainable paper-based packaging materials while maintaining their biodegradability characteristics.

Keywords: *Biodegradability; Biopolymer; Nanomaterial; old corrugated containers pulp; Virgin Bleached wood Pulp*

1. Introduction

Paper and paper-based material are widely used across packaging, printing, food services, art & creative crafts, decor and stationary etc. as compared to their plastic counterpart because of the properties offered e.g. recyclability, renewability, sustainability, biodegradability and environmental friendliness (1).

The global paper packaging market size was estimated at USD 416.07 billion in 2025 and is expected to reach USD 611.66 billion by 2033, growing at a CAGR of 5.0% from 2026 to 2033 (2).This growth is driven by a rising demand for sustainable packaging solutions as consumers and businesses, increasingly prioritize eco-friendly options. Paper consists of cellulose fiber which is a renewable, recyclable and biodegradable polymer but rate and extent of its degradation depends upon composition and surface modifications done on paper.

There is high demand of paper and paper-based material in packaging industry but without required modifications of paper its use as packaging material become inadequate (1). Therefore, different types of modifications e.g. surface modifications, wet end modifications are carried out on paper to make it as appropriate packaging material but these modifications also alter the biodegradability nature of paper and raises concerns over its environmental impacts in terms of waste generation and its degradability.

Biodegradability is the capacity of a material to be broken down and decomposed by the natural metabolic or enzymatic action of living organisms (enzyme, bacteria, fungi etc.) into simpler, non-toxic components such as carbon dioxide, water and biomass. Factor such as fibre source (wood based, agro based, recycled etc.), coating material, surface sizing, lamination etc. can affect the biodegradation behaviour of paper-based packaging material. For example, recycled pulp such as OCC can show different behaviour as compared to virgin pulp.

In the recent years, different types of additives are used for surface modification of paper to enhance its functional properties like surface properties, strength properties and barrier properties etc. The synthetic and non-biodegradable polymer has been widely used as additives for modification of paper but most of them are non-biodegradable and possess serious threats to environment and human health as shown in table 1. Which motivates researchers to explore eco-friendly additives to reduce dependence on petroleum derived chemicals (3-5).

Table 1: Synthetic polymers used in papermaking and paper coating and the possible risks associated

S.No.	Name of polymer	Effect on		Reference
		Human health	Environment	
1.	Acrylic coatings	Residual monomers and additives can migrate into food; some acrylates may irritate skin and respiratory system	Poor biodegradability; aquatic toxicity from coating residues	10
2.	Polyethylene (PE, LDPE, HDPE)	Generally considered low toxicity, but additives and degradation products may migrate into food; possible exposure to micro-plastics and additives during heating	Non-biodegradable; difficult to recycle when bonded to paper; contributes to micro-plastic pollution	11
3.	PFAS / Fluorochemical coatings	Linked to endocrine disruption, immune suppression, developmental toxicity, liver effects, and possible cancers; migrate into food	Forever chemicals, highly persistent, bio-accumulative, contaminate soil and water	12
4.	Polyamines	Elevated levels have been associated with breast, colon, lung, prostate and skin cancer	Aquatic toxicity, Formation of chlorinated by products, Poor biodegradability, Persistence in sludge	3
5.	Urea formaldehyde	Releases formaldehyde that can cause skin, eye, nose, throat irritation, allergic reaction	Air pollution, Aquatic toxicity, Microplastic-like persistence, Toxic manufacturing waste	3

Figure 1 illustrates the major classes of biodegradable polymers, categorized into natural polymer like Protein based biopolymer (PBP), Polyester based biopolymer (PYBP), and polysaccharide based biopolymer (PSBP). Starch, one of the most widely used biodegradable polymers that improves strength properties of paper (6) and extensively applied to improve properties of different pulp furnishes like hardwoods, softwoods, recycled pulp (7, 8). Starch, mainly consist of two homo polysaccharides i.e. linear amylose having α-D-glucose units connected byα-1,4 glycosidic linkage and branched amylopectin havingα-1,4-glycosidic linkages in its main chains andα-1,6-glycosidic linkages at branch points that leads to unique properties of gelatinization and retrogradation to polymer cleaner approach (9).

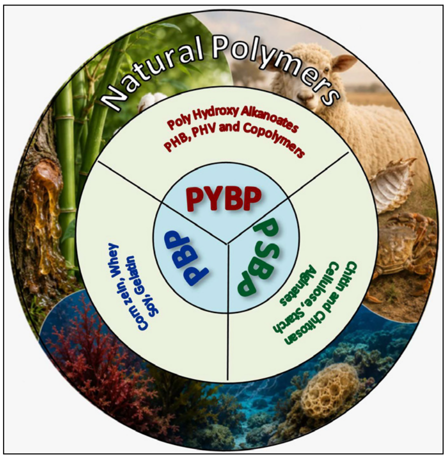

Figure 1: The major classes of biodegradable polymers

Therefore, application of such coating material affects biodegradability behavior of paper by altering the interaction between cellulose and microorganism that leads to increase in the time required for degradation and decrease in the extent of degradation.

Despite common adoption of coating material in paper industry, there is very less comparative study is available that how different type of coating material and papers affects the rate of biodegradability behavior of coated paper in natural soil conditions. This gap highlights the need of systematic investigation that how different type of paper and coated paper behaves under similar conditions.

The present study focuses on biodegradability behavior of different type of paper materials (wood and OCC based paper). In addition to comparing different fiber sources this study specifically investigates the effect of coating material on extent of biodegradability whether such coating accelerate, delay the degradation behavior of paper in soil.

The findings of this study develop better understanding that how raw material composition, surface modifications and different fiber sources affect extent and rate of biodegradation. This study can help in development of more sustainable and environmentally friendly packaging material by selection of appropriate coating material and ultimately it helps industries and policymakers regarding development of eco-friendly material and to solve waste management problems.

2. Material and methods

2.1 Materials

Bleached hardwood pulp was donated by an integrated pulp and paper mill situated in North India for this study. Old corrugated containers (OCC) were collected from a waste paper recycling unit situated in North India. OCC pulp was prepared in laboratory using high-consistency hydrapulper.The compost used in this study was taken from CPPRI Horticulture department.

2.2 Methods

Initially, the dryness of the samples was determined according to the Technical Association of the Pulp and Paper Industry standard method (TAPPI) T 412 om-16. The sample was weighed to obtain its initial weight and then dried in a hot air oven at 105 ± 2°C until a constant weight was achieved. After drying, the sample was cooled in a desiccator and weighed again to determine the oven-dry weight. The percentage dryness was calculated using the following formula:

Dryness (%) = (Oven-dry weight/ Initial wet weight) *100

2.3 Preparation of Pulp from OCC and Paper Hand-sheet

Initially, the OCC material was manually torn into smaller pieces to facilitate the pulping process. The smaller pieces of sample were then processed in a high consistency laboratory pulper (UEC-2024) of universal engineering corporation, Saharanpur (Uttar Pradesh). The pulping was done at 10% consistency under ambient condition for 30 minutes using high consistency hydra pulper. The pulping slurry was screened using a Sommerville vibratory screen having a 0.15 mm slot to remove unwanted contaminants and coarse particles.

For both pulp furnish, the hand-sheets of 100±1 g/m2was made using British hand-sheet Former as per standard method (TAPPI T 205 sp-02). The sample for biodegradability testing was prepared by cutting hand-sheets to the equal rectangular size of 3*3 cm. Each sample, whether made from OCC or wood pulp, was noted for its respective weight and a unique identification code was given for proper identification.

2.4 Biodegradability Test

The soil biodegradation test by weight loss method (EN 14045:2003) was carried out to determine the biodegradability of a material in soil under controlled environmental conditions. In this method, the test sample is buried in biologically active soil, and the loss in weight of the sample after a specific time period was measured. The change in weight indicates the extent of biodegradation caused by microorganisms present in the soil.

The agricultural soil is collected and unwanted particles like large sized stone, plastic waste etc. were removed manually. The initial weight of different uniform sized test samples was measured using analytical weighing balance. Clean 500 ml capacity beakers are filled with the collected agricultural soil. The samples were buried at a depth of about 5 to 6 cm below the soil surface of the beaker. The beakers are kept under controlled laboratory conditions at a temperature of approximately 25 ± 2°C. Soil moisture is maintained throughout the experiment by periodically adding water if required.

The buried paper samples in soil were weighted periodically. At the end of each time period, the samples are carefully removed from the soil. The attached soil particles are gently washed off with distilled water, and the samples are dried again in an oven at the temperature (105 ± 2°C) until constant weight is obtained. After drying, the samples were cooled in a desiccator and weighed accurately to determine the final dry weight.

The percentage weight loss, which represents the biodegradation of the material, is calculated using the following formula:

% Weight Loss= (W0 – Wt) / W0*100

Where,

- W0 = Initial dry weight of sample
- Wt = Final dry weight after soil exposure

A higher percentage of weight loss indicates greater biodegradation of the material in soil.

3 Results and Discussion

In the present study, the biodegradability of papers produced from OCC pulp and wood pulp, with and without surface sizing treatments incorporating pro-microbial and antimicrobial biopolymers, was investigated. The findings demonstrated significant variations in the degradation rates of the differently surface sized papers throughout the experimental period.

3.1 Biodegradation of paper made by using OCC and wood pulp

OCC pulp demonstrated substantially faster degradation than bleached wood pulp, reaching complete degradation (100%) within 4 to 6 weeks, whereas wood pulp required 8 to 12 weeks to achieve the same level of decomposition. The OCC pulp showed a rapid initial degradation phase, increasing from approximately 13 to 15% degradation in the first week to about 45% by the second week and 85% by the fourth week as shown in Table 2. However, wood pulp exhibited a slower degradation pattern, with only 4% degradation in the first week and 10 to 12% in the second week, indicating an initial lag phase. Although degradation of wood pulp gradually increased over time, reaching 65 to 70% by sixth week and 85 to 90% by eighth week. These results indicate that paper made from OCC pulp showed faster biodegradability in comparison to paper made from bleached wood pulp.

Table 2: Biodegradability of hand-sheets made by using OCC and wood pulp without surface sizing

Sample/ Time period (week)	Biodegradability rate of paper (%)	
	OCC pulp based paper	Wood pulp based paper
1	8-10	4-6
2	40-45	10-12
4	80-85	30-35
6	100	65-70
8	-	85-90
12	-	100

The enhanced biodegradation kinetics observed in OCC pulp compared to virgin wood pulp can be attributed to the structural and morphological modifications induced by repeated pulping, papermaking, and recycling processes. Mechanical shearing, coupled with successive drying and rewetting cycles, reduces fibre length, weakens fibre integrity, and causes cell wall damage, resulting in shorter and more fragmented fibres with a more open and porous structure. These changes increase the specific surface area, expose a greater number of cellulose chain ends, and enhance the accessibility of cellulose to microbial enzymes, thereby promoting microbial attachment, colonization, and enzymatic hydrolysis. In addition, OCC pulp may contain residual organic constituents, such as hemicelluloses, starches, and other papermaking additives, which can serve as supplementary nutrient sources for microorganisms and further stimulate microbial activity during soil burial. The increased porosity and moisture-holding capacity of OCC based paper also create favorable conditions for microbial growth and degradation. Consequently, microorganisms can more readily penetrate and decompose the fibre matrix, resulting in significantly accelerated biodegradation. In contrast, virgin wood pulp fibres retain a higher degree of structural integrity and form a denser, more compact fibre network that restricts microbial penetration and enzymatic access to cellulose. Therefore, paper produced from virgin wood pulp exhibited a relatively slower degradation rate than paper manufactured from OCC pulp.

3.2 Biodegradation of Surface Sized paper made by using OCC and wood pulp

3.2.1 Pro-microbial coated sample

The biodegradation behaviour of pro-microbial coated pulp showed a rapid increase in degradation rate for both recycled pulp and wood pulp based paper over the period. During the first week, recycled pulp based paper exhibited 18 to 20% degradation, while wood pulp based paper showed a slightly lower degradation of 12 to 15%. From the second week onwards, degradation of recycled pulp based paper increased sharply to 85 to 90%, compared to 45 to 50% for wood pulp based paper, indicating a significantly faster decomposition rate of OCC pulp based paper as shown in Table 3. Complete degradation (100%) of recycled pulp based paper was achieved within 4 weeks, whereas wood pulp based paper reached only 70-75% degradation within 4 weeks. Complete degradation of wood based paper takes approximately 6 weeks. These results demonstrate that the pro-microbial coating effectively accelerates biodegradation in both substrates i.e. OCC and wood based paper as compared to their control set i.e. uncoated paper. By the addition of nano material along with pro microbial biopolymer during surface sizing decreased the degradation rate of both the types of paper as shown in table 3.

Table 3: Biodegradability of hand-sheets made by using OCC and wood pulp with surface sizing using promicrobial biopolymer alone and with nano-material

Sample/Time period (week)	Biodegradability rate of paper (%)			
	OCC pulp based paper		Wood pulp based paper	
	Pro-microbial coated	Pro-microbial + nano-coated	Pro-microbial coated	Pro-microbial+ nano coated
1	18-20	12-14	12-15	5-8
2	85-90	60-65	45-50	35-40
4	100	80-85	70-75	60-70
6	-	100	95-100	85-90
8	-		-	100

The faster degradation observed in the pro-microbial coated samples may be attributed to the sizing material ability to promote microbial colonization and activity on the fiber surface. Pro-microbial sizing material helped to create favourable conditions for naturally occurring microorganisms such as bacteria and fungi, which produces enzymes capable of breaking down cellulose, hemicellulose, and other organic components of pulp fibres. As microbial growth increases, the enzymatic degradation of the fibre matrix accelerates, resulting in a rapid loss of structural integrity and faster biodegradation.

Additionally, pro-microbial coatings may enhance moisture retention and surface wettability, facilitating microbial attachment as a result OCC pulp showed even faster degradation than wood pulp because recycled fibres generally possess, shorter fibre length, and a more porous structure due to previous processing cycles, making them more accessible to microbial attack. Consequently, the synergistic effect of the pro-microbial coating and the higher susceptibility of recycled fibres led to the highest degradation rates observed in the study. The decreased degradation rate observed upon nanomaterial addition may be attributed to the filling of pores within the paper matrix, which substantially reduces paper porosity. The reduced porosity restricts moisture uptake and microbial access to the fibre network, thereby retarding biodegradation.

3.2.2 Antimicrobial coated samples

In contrast, antimicrobial coated paper samples exhibited a much slower degradation pattern throughout the study period. OCC pulp based paper showed only 5-7% degradation after one week and it increased gradually to 25 to 30% after 2 weeks and 52 to 55% after 4 weeks as shown in Table 4. Complete degradation of OCC pulp based paper was observed after 8 weeks. Wood pulp displayed an even slower degradation rate. It showed 4 to 5% degradation after 2 weeks, 15 to 18% after 4 weeks, and 38 to 40% after 6 weeks as shown in Table 4. The degradation continued progressively to 85 to 90% after 12 weeks, and finally 95 to 98% after 16 weeks. Compared with recycled pulp, wood pulp exhibited greater resistance to biodegradation under antimicrobial coating conditions. Overall, the antimicrobial coating significantly delayed degradation in both types of paper, extending the decomposition period relative to the corresponding pro-microbial coated samples and uncoated paper samples. By the addition of nano-material along with antimicrobial biopolymer during surface sizing decreased the degradation rate of both the types of paper as shown in table 4.

Table 4: Biodegradability of hand-sheets made by using OCC and wood pulp with surface sizing using antimicrobial biopolymer alone and with nano-material

Sample/Time period (week)	Biodegradability rate of paper (%)			
	OCC pulp based paper		Wood pulp based paper	
	Anti-microbial coated	Anti-microbial coated+ nano	Anti-microbial coated	Anti-microbial coated+ nano
1	5-7	-	-	-
2	25-30	10-15	4-5	-
4	52-55	30-35	15-18	5-10
6	75-80	50-55	38-40	20-25
8	100	65-70	60-65	50-55
12	-	80-85	85-90	75-80
16	-	100	95-98	85-90
18				100

The slower degradation of anti-microbial coated samples is primarily due to the coating's ability to inhibit the growth and activity of microorganisms responsible for biodegradation. It may be assumed that antimicrobial biopolymer suppress microbes (bacteria, fungi, etc.) that produce cellulolytic enzymes required to break down cellulose fibres. As a result, microbial colonization on the paper surface is reduced, leading to a lower rate of enzymatic degradation and a slower decomposition process.

Furthermore, antimicrobial coatings may act as a protective barrier on the fibre surface; limiting moisture penetration and reducing direct contact between microorganisms and the cellulosic fibres. This decrease in direct contact between microorganisms and the cellulosic fibres delay the cellulosic fibre breakdown. The wood pulp based paper exhibited even slower degradation than recycled pulp may be due to this reason that wood fibres generally have a more intact fibre structure, making them naturally more resistant to microbial attack. Therefore, the combined effect of the antimicrobial coating and the inherent resistance of wood pulp fibres resulted in the prolonged degradation period observed in the study. The reduction in the degradation rate following the incorporation of nano-materials may be attributed to their ability to occupy and seal the pores within the paper structure, thereby significantly decreasing the overall porosity of the paper. The resulting denser fibre network limits moisture penetration, microbial colonization, and enzymatic accessibility to cellulose, ultimately slowing the biodegradation process.

4 Limitations/Future Work

A limitation of the present study is the absence of morphological characterization of the degraded samples using scanning electron microscopy (SEM). Such analysis could provide direct evidence of fibre surface deterioration, microbial attack, and structural changes occurring during biodegradation. Future studies will incorporate SEM and other advanced analytical techniques to gain deeper insight into the degradation mechanisms of surface-modified paper materials. The biodegradation assessment in the present study was performed using the soil burial method based on weight loss measurements, which provides a practical means of comparing the relative degradation behaviour of different paper formulations. However, weight loss may reflect both biological degradation and physical disintegration of the material. Therefore, the results should be interpreted as comparative degradation performance rather than ultimate biodegradation. Future studies should employ standardized methods such as ASTM D5338, based on CO_2 evolution, to quantify the degree of mineralization and provide a more comprehensive assessment of biodegradability.

Conclusion

The biodegradation study demonstrates that both the inherent pulp type and subsequent surface treatments are critical factors in deciding the rate of material decomposition. Among the untreated samples, OCC pulp based paper exhibits a substantially accelerated degradation rate compared to virgin wood pulp.

Surface sizing further affects the degradation kinetics. Pro-microbial coatings accelerate decomposition for both paper types by enhancing surface wettability, improving moisture retention, and promoting rapid microbial colonization and localized enzymatic activity.

On the other hand, antimicrobial coatings effectively introduce a protective barrier that suppresses microbial growth and hamper enzymatic breakdown of the fiber matrix, significantly delaying fiber degradation.

Overall, the results indicate that OCC pulp based paper possesses inherently higher biodegradability than virgin wood pulp. Pro-microbial coatings can effectively enhance biodegradation and may be suitable for environmentally friendly disposable packaging applications where rapid end-of-life degradation is desired. However, antimicrobial coatings can extend material durability and service life by delaying microbial degradation, making them suitable for applications requiring prolonged product stability. These findings provide valuable insights for designing sustainable fibre-based packaging materials with tailored biodegradation performance. By the addition of nano-material along with pro/anti-microbial biopolymer during surface sizing decreased the degradation rate of both the types of paper.

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