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ARTICLE

Banana Peel and Beyond: Transforming Agricultural Waste into Eco-Friendly, Biodegradable Plastics

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ABSTRACT

The management of agricultural wastes is essential for resource conservation and environmental sustainability. Due to escalating worries regarding plastic pollution and the surging expenses linked to petroleum-based plastics, there has been a notable transition towards the creation of biodegradable alternatives sourced from natural materials. Biofibres and bioplastics, especially those derived from agricultural waste, have garnered significant attention for their prospective uses

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in food packaging, biomedical sciences, and sustainable manufacturing. This study examines the viability of employing banana peel as a natural and environmentally sustainable raw material for the production of biodegradable bioplastic sheets. Due to its abundant polysaccharides and lignocellulosic fibers, banana peel presents advantageous structural and mechanical characteristics for bioplastic manufacturing. Experimental findings demonstrate that bioplastic derived from banana peels has enhanced biodegradability and environmental compatibility relative to traditional synthetic plastics, positioning it as a feasible alternative to mitigate the worldwide plastic waste epidemic. An optimal formulation was constructed using Design Expert software, comprising 55.38 g of banana peel, 27.63 g of fish scales, and 20 g of chitosan powder. This formulation improves the film's tensile strength, flexibility, and degradation rate, ensuring its efficacy in industrial applications including food packaging and molding. The study's results highlight the promise of bioplastics made from banana peels as an economical and sustainable alternative, decreasing dependence on petroleum-based plastics and alleviating environmental pollution.

Keywords: Biodegradable Plastics Banana Peel; Fish Scale; Chitosan; Design Expert Software

1. Introduction

The investigation of sustainable materials, especially bio-based plastics, has garnered heightened interest owing to the urgent environmental issues associated with synthetic plastics. Traditional plastics, predominantly derived from petroleum sources, substantially contribute to pollution, carbon emissions, and the accumulation of non-biodegradable trash. The extensive utilization of synthetic plastics has elicited apprehensions regarding their whole life cycle, encompassing monomer synthesis, manufacturing procedures, and disposal and recycling difficulties. As a result, there is an increasing transition towards bio-based plastics sourced from renewable and biodegradable materials as a sustainable alternative.

1.1. The Manufacturing and Ecological Consequences of Synthetic Plastics

Traditionally, plastics are produced from organic and natural resources such as natural gas, coal, cellulose, salt, and crude oil. Crude oil, a complex amalgamation of hydrocarbons, is refined prior to its utilization as a feedstock in plastic manufacturing. The initial phase of the production process entails the distillation of crude oil at a refinery to segregate it into distinct fractions according to molecular size and structure. Naphtha is the principal raw ingredient for plastic production among these components [1, 2].Plastic manufacture encompasses two principal processes—polymerization and polycondensation—both reliant on particular catalysts. Plastics consist of long-chain molecules called polymers, which are formed from repeating monomer units. These polymeric structures confer plastics advantageous characteristics, including low weight, durability, and mechanical strength. Nonetheless, these identical characteristics render plastics environmentally detrimental, as they do not degrade readily.The worldwide output of synthetic plastics has increased significantly during the last century, especially after World War II. The widespread production of plastics transformed other industries, such as medical, transportation, space exploration, and consumer products. Plastics have become essential in contemporary civilization, ranging from life-saving medical devices and protective equipment to lightweight car parts and food packaging. Notwithstanding their advantages, synthetic plastics present considerable environmental hazards owing to their durability and role in global pollution.

1.2. The Issue of Disposable Plastics

A significant worry regarding synthetic plastics is the proliferation of single-use plastics, which constitute over 45% of all plastic manufactured each year. Single-use plastics, like food wrappers, plastic bags, and disposable cutlery, possess a brief functional duration yet can last in the environment for centuries. Their extensive utilization and inappropriate disposal lead to significant environmental degradation, including ocean pollution, wildlife harm, and soil and water body contamination.The non-biodegradable characteristics of petroleum-derived polymers intensify waste management issues. Plastics deteriorate by photodegradation and chemical decomposition, resulting in the release of hazardous by-products and microplastics into ecosystems. The proliferation of plastic garbage in landfills and aquatic ecosystems has resulted in considerable ecological repercussions, including disturbances in the food chain and risks to biodiversity.The manufacture of polymers from fossil fuels significantly contributes to carbon emissions. The projected daily usage of crude oil for plastic packaging manufacturing surpasses 420,000 barrels worldwide, underscoring the sector's reliance on limited fossil fuel reserves. With the increasing worldwide awareness of climate change and environmental sustainability, industry and researchers are investigating alternate alternatives to diminish dependence on traditional plastics [3, 4].

1.3. The Rise of Bioplastics as a Sustainable Substitute

Bioplastics, originating from biodegradable and renewable resources, offer a viable remedy to the ecological issues linked to petroleum-derived plastics. In contrast to traditional plastics, bioplastics are engineered to decompose spontaneously, hence reducing prolonged pollution and environmental damage.Bioplastics can be synthesized from diverse agro-waste sources, such as potato peels, fruit remnants, banana peels, and other plant-derived materials. These raw materials are plentiful, cost-effective, and abundant in polysaccharides, cellulose, and other biopolymers suitable for plastic manufacturing. Bioplastics are biodegradable and devoid of toxic chemicals and poisons typically included in synthetic plastics, rendering them a safer option for uses such as food packaging and biomedical products.The advancement of bioplastics is affected by the accessibility and expense of raw ingredients. Nations with elevated agricultural productivity, like India and China, have considerable potential to excel in the manufacture of fruit- and vegetable-derived biopolymers. These countries generate significant amounts of agro-waste, which can be efficiently employed to produce bioplastics, aiding in waste reduction and the advancement of sustainable materials.

1.4. Benefits of Bioplastics Derived from Banana Peels

Among many agro-waste sources, banana peels have emerged as a suitable raw material for bioplastic manufacturing owing to their abundant content of natural polymers, such as starch and cellulose. Bioplastics derived from banana peels have numerous benefits:Biodegradability: Banana peel bioplastics naturally disintegrate, mitigating the buildup of plastic waste in landfills and oceans.Environmental Compatibility: In contrast to synthetic plastics, bioplastics made from banana peels do not emit hazardous toxins or microplastics during breakdown.Mechanical Strength: Experimental investigations indicate that films derived from banana peels demonstrate enhanced tensile strength and flexibility relative to other biodegradable materials [5]. Sustainability: Employing banana peels for bioplastic manufacturing enhances waste valorization, converting agricultural byproducts into useful assets [6].

1.5. Enhancement of Bioplastic Composition Derived from Banana Peels

Recent studies have concentrated on enhancing bioplastic formulations derived from banana peels to improve their mechanical and biodegradability characteristics. An optimum formulation, established by Design Expert software, comprises:

55.38 grams of banana peel

27.63 grams of fish scales

20 grams of chitosan powder

This formulation demonstrates enhanced tensile strength and biodegradability, rendering it appropriate for industrial applications including food packaging and moulding. The incorporation of fish scales and chitosan enhances the bioplastic's resilience and functional characteristics, affirming its viability as a commercial substitute for petroleum-derived polymers.

1.6. Anticipated Opportunities and Obstacles

Despite the significant potential of bioplastics, numerous obstacles persist regarding their widespread implementation. The production cost, scalability, and performance of bioplastics under various environmental conditions are essential elements requiring more examination. Moreover, advancing efficient processing methods and enhancing bioplastic durability without sacrificing biodegradability are essential study domains.Future developments in bioplastic technology may concentrate on improving the characteristics of bio-based films via nanotechnology, reinforcement with natural fibers, and hybrid material compositions. Governments and companies must work to design regulations, incentives, and infrastructure that promote bioplastic production and acceptance.

1.7. Chemical Composition of Banana Peel

It has been shown that banana peel contains many nutrients and minerals. They found crude proteins in the amount of 1.95 ± 0.14%, crude fat 5.93 ± 0.13%, and 11.82 ± 2.17% carbohydrate in the banana peel. The mineral composition of banana peel includes phosphorus, iron, calcium, magnesium, and sodium. Zinc, copper, potassium, and manganese were found in very low concentrations at 76.20 mg g^{-1} [7–9].

1.8. Proof of Identity of the Need & Problem Description

This study addresses an eco-friendly plastic replacement that poses no threat to living beings. This plastic is biodegradable and sourced from banana peel remnants (Musa), augmented with additional catalysts that improve its characteristics, rendering it appropriate for many uses and beneficial even post-decomposition. This bioplastic, in contrast to traditional polymers derived from petroleum, is cost-effective, adaptable, and readily biodegradable, mitigating significant environmental issues related to plastic pollution. India is the third-largest user of plastics, utilizing billions of plastic goods each year. The pervasive utilization of petroleum-derived plastics substantially exacerbates pollution and environmental deterioration. A primary concern about traditional plastics is their disposal. The combustion of petroleum-based polymers emits carbon dioxide and other detrimental pollutants into the atmosphere, intensifying global warming. Moreover, these plastics are non-biodegradable and endure in the environment for centuries, resulting in significant ecological repercussions, including soil and water pollution and the disturbance of marine and terrestrial ecosystems.The rising amount of plastic garbage is concomitantly exacerbating environmental issues. The proliferation of plastic garbage in landfills and ecosystems endangers biodiversity and human health. Furthermore, petroleum, a fundamental raw element in traditional plastic manufacturing, is a non-renewable resource. The dependence on petroleum for plastic production exhausts natural supplies, and the ephemeral nature of these plastics—typically utilized for a short duration before disposal—exacerbates the problem.Recycling and processing petroleum-derived plastics are expensive and ineffective remedies for the pollution issue. Although recycling helps alleviate certain environmental effects, it fails to tackle the fundamental cause of plastic pollution. The melting and reprocessing of plastic produce supplementary pollutants and hazardous by-products, exacerbating environmental damage. Conversely, bioplastics sourced from banana peels offer a sustainable and environmentally favorable option. These bioplastics undergo natural decomposition, diminishing the long-term environmental impact and providing a feasible resolution to the worldwide plastic dilemma. The utilization of biodegradable alternatives, such as bioplastics derived from banana peels, offers a means to reduce pollution, conserve resources, and foster a circular economy for sustainable development [10–13].

Chemical synthesis methods for producing bioplastics often involve treating agro-waste or food residues with acids and alkalis to extract key components such as lignin and cellulose. These processes introduce functional groups (e.g., C = O, C-O-C) that influence the mechanical properties of the biopolymer by enhancing the strength of chemical bonds. However, this chemical treatment can lead to byproducts such as furan derivatives, carboxylic acids, and lignin-derived phenols, which can inhibit enzymatic activity crucial for subsequent fermentation stages [14].

Bananas, which belong to the Musaceae family and the Musa genus, are cultivated in over 145 countries. Their peels contain approximately 30% starch, a primary component, along with high carbohydrate content. Starch, a polymer made of long chains of glucose molecules, is highly versatile and can be used to create plastic-like materials. For instance, corn starch, composed of 70–80% amylopectin and 20–30% amylose, can be processed into plastic films that are non-toxic, odourless, colourless, and tasteless. These films can either be formed by physically combining starch granules or blending them on a molecular level with other polymers [15–18].

Similarly, banana peel starch can be used to create bioplastics sourced from renewable materials or organic biomass. Through chemical and mechanical processes, cellulose nanofibers can be extracted from banana peels and incorporated into nanocomposites. The inclusion of these nanofibers strengthens the bioplastic, enhancing its tensile strength, water resistance, and thermal stability. By using both starch and cellulose nanofibers from unripe banana peels as a matrix and reinforcing agent, biodegradable films can be produced, making them well-suited for food packaging due to their biocompatibility, biodegradability, and non-toxic properties[19].

This research emphasizes the potential of bioplastics to mitigate the environmental issues associated with non-degradable plastics. Bioplastics help protect the environment by preventing synthetic plastic waste from polluting air, water, and ecosystems. Derived from renewable biomass, they present an eco-friendly alternative to traditional petrochemical plastics. The aim of this research is to develop bioplastics from banana peels with properties comparable to conventional petro-plastics like polypropylene. The target product is envisioned to be fully waterproof, capable of withstanding high temperatures for diverse applications, and 100% biodegradable, ensuring minimal environmental impact. Successful development of such a bioplastic would decrease reliance on petroleum-based plastics, expand its potential applications across industries, and contribute to reducing environmental pollution. The objective of this study is to produce biodegradable plastic from banana peels as a substitute for conventional plastic and to prove that the starch in the banana peel could be used in the production of biodegradable plastic. The strength of the film was determined using the elongation test by comparing the biodegradable film with a control film and a synthetic plastic. In the soil burial degradation test, the intensity of degradation was tested for all three types of film and the biodegradable film degraded at a rapid rate compared to the control film while the synthetic plastic did not degrade at all. Based on all the testing that was carried out, the biodegradable film from banana peel is the best and ideal overall compared to the control and synthetic plastic. The films were prepared successfully by the mixing and casting method. The characteristics of the films with different glycerine content (20 ml, 25 ml, and 30 ml) were evaluated using the soil burial degradation test and manually. In the soil burial degradation test, the compactness of biodegradable composite films was destroyed as the degradation time increased. A rapid degradation occurred for all the films in the initial 6 days, followed by 100% composting within the expected 90 days. As a conclusion, the films produced from banana peels had potential applications to be used as food packaging because they can enhance food quality and at the same time can protect the environment[20, 21].

2. Materials and Methods

2.1. Materials

Beakers, Wash Bottle, Thermometer, Stirring Rod, Glycerol, NaOH, Citric acid, HCl, Banana peel.

2.2. ASTM D638

It is a standard test method for determining the tensile strength, yield point, modulus of elasticity, and ultimate plastic elongation using a standard formed specimen. The tensile strength will be determined using an ASTM standard machine. The material's tensile strength is negligible in the absence of starch and rises in the presence of starch. The sample values of three components, Banana peel, Fish scale, and Chitosan, are shown in **Table 1**[22, 23].

2.3. Methodology & Experimental Procedure

The first process entails preparing banana peels for starch extraction following the procurement of bananas from a local market in Seeb. The banana peels were meticulously excised using a scalpel and subsequently sectioned into diminutive fragments. A 200 ml beaker was utilized to measure the peels precisely, with recorded sample weights of 13.5 g, 13.6 g, 15 g, 15 g, 15 g, and 12.45 g, respectively. Each sample was subjected to 5 ml of 1N citric acid and allowed to incubate for 25 minutes. Citric acid functions as an antioxidant and microbiological inhibitor, substituting sodium metabisulfite with comparable effectiveness while improving the biodegradability of plastic over time.The peels immersed in citric acid were thereafter placed in a 100 ml beaker filled with distilled water. The mixture was heated on a computerized magnetic hotplate stirrer with a ceramic surface for 25 to 35 minutes. The regulated boiling process enables the decomposition of complex carbs, liberating starch into the solution. Acid hydrolysis modifies the physicochemical characteristics of starch while preserving its granular structure. The temperature and duration of this procedure

Table 1. Proportions of banana peel, fish scale, and chitosan used in sample mixes.

Run	Component 1 A: Banana Peel (g)	Component 2 B: Fish Scale (g)	Component 3 C: Chitosan (g)
1	13.50	6.25	4.97
2	13.60	7.50	3.74
3	15.00	7.50	2.50
4	15.00	6.24	3.75
5	15.00	5.00	5.00
6	12.45	7.50	5.00

were refined to enhance starch recovery while preserving its integrity for subsequent bioplastic manufacture. A reduced amylopectin level in starch is associated with enhanced starch recovery, rendering it a vital determinant in the quality of the final bioplastic material.Fish scales were manufactured by meticulously cleaning them to eliminate contaminants, then drying them in an oven at a temperature between 40–75 °C. The drying process facilitates the elimination of surplus moisture, which could otherwise compromise the blending and structural integrity of the bioplastic. Upon drying, the fish scales were pulverized into a fine powder to provide homogeneous integration with the banana peel starch extract and chitosan powder. The desiccated fish scales were subsequently amalgamated with chitosan powder according to the precise ratios specified for each sample, thus guaranteeing uniformity and replicability in the formulation procedure. Chitosan, a biopolymer sourced from chitin, significantly improves the mechanical strength and biodegradability of bioplastic materials.The resultant combination was subjected to additional processing to attain homogeneity and enhance the material's structural qualities. Stirring at regulated temperatures facilitated the even dispersion of components, resulting in the creation of a homogeneous polymer network. The resultant slurry was subsequently poured into molds for drying, where it experienced a regulated drying process to harden into bioplastic sheets. The drying phase was crucial for achieving a resilient and pliable bioplastic sheet with superior tensile strength and degradation properties. Upon complete drying, the bioplastic samples were meticulously extracted from the molds and preserved under regulated settings to avert contamination and moisture uptake. The resultant bioplastic was assessed according to critical parameters like tensile strength, biodegradability, and structural integrity, confirming its compliance with requisite performance standards for prospective industrial applications.The procedure was engineered to increase starch extraction efficiency, improve biodegradability, and enhance the mechanical qualities of the bioplastic material. **Table 2** [24] presents the specific mixing ratios for each sample along with their associated attributes.

Table 2. Fish sample and chitosan powder compositions in corresponding runs.

#	Fish Sample	Chitosan Powder
1	6.15	4.95
2	7.25	3.68
3	7.25	2.45
4	6.30	3.65
5	5.00	5.25
6	7.25	5.25

The mixture is distributed on aluminum and entered into the oven at different temperatures from 92 to 190 °C for 1 hr. After that, it is left to cool for varying hours from 4 to 7.5 hrs.

2.4. Assessment Methods

2.4.1. Estimation of Tensile Strength

A specimen measuring 2.0 cm by 6.0 cm is extracted and subjected to tensile testing utilizing a tensile strength elongation apparatus. The film is progressively elevated to its maximum height to assess its mechanical qualities, particularly its tensile strength and elongation characteristics. As the specimen is elongated, its diameter diminishes while its length progressively grows. The tensile strength elongation tester exerts a regulated force on the specimen until it attains its fracture threshold. The length extension and applied load are continuously monitored to assess the material's mechanical reaction to stress.The tensile strength of the bioplastic sheet is subsequently determined using the formula:Tensile strength is calculated as Fmax divided by A0.where Fmax represents the maximum force applied before the film breaks, and A0 is the initial cross-sectional surface area of the sample in square meters. This measurement offers insight into the resilience and structural integrity of the bioplastic material. Increased tensile strength signifies enhanced resistance to mechanical stress, an essential characteristic for practical applications like packaging and biodegradable materials. The results obtained facilitate the optimization of the bioplastic composition to enhance mechanical performance [25].

2.4.2. Biodegradability Test (Soil Burial Method)

The soil burial test offered a realistic setting for evaluating biodegradability, influenced by seasonal fluctuations in soil moisture, temperature, and microbial activity under less controlled conditions. This method accurately replicated real-world deterioration conditions, providing significant insights into the material's environmental effects. To maintain consistency, all evaluated films were fabricated in uniform shapes and dimensions, hence removing the impact of film geometry on degrading characteristics. The films were interred in the soil, and their mass reduction was assessed by sampling at regular intervals. Assessments were performed bi-daily to evaluate the degree of disintegration throughout time [26, 27]. The findings indicated a sustained rise in the breakdown rate of banana peel starch films as the duration of exposure extended. The biodegradable bio-composite films exhibited rapid degradation, signifying a significant vulnerability to microbial and environmental influences. Initially, it was anticipated that all films would complete the degrading process within 90 days according to preliminary estimations. Under the specified test circumstances, the films were found to completely decompose within 15 days, demonstrating their exceptional biodegradability. These findings underscore the promise of banana peel-derived bioplastics as an efficient and sustainable substitute for traditional plastics, aiding in the mitigation of environmental impact.

3. Results and Discussion

The test samples after the drying process are established, and the biodegradation test results of bioplastic samples are reported in **Table 3**.

Table 3 reveals that Sample 1 underwent the highest percentage of weight reduction, followed by Sample 2, while Sample 5 had the minimal weight loss. Samples 3, 4, and 6 exhibited modest weight loss rates, with Sample 3 showing a slightly higher rate than Sample 4, but Sample 6 recorded the lowest weight loss in this group. Sample 1 demonstrated the highest breakdown rate at 78.235%, whereas Sample 5 revealed the lowest rate at 38.45%.Sample 1 consisted of 55.35 g of banana peel, 20 g of chitosan, and 25.35 g of fish scales. Following the soil burial test, the mass of Sample 1 diminished to 22.75 g, indicating successful decomposition without producing harmful residues. The significant weight reduction observed in Sample 1 suggests that its composition facilitates rapid biodegradation within a short timeframe. This result underscores the effectiveness of bioplastics sourced from banana peels in alleviating plastic pollution by providing a biodegradable alternative to petroleum-based plastics. Similarly, Sample 2 demonstrated a notable percentage of weight loss, signifying its ability for fast decomposition. In contrast, the diminished weight loss percentage of Sample 5 suggests that its composition may require a prolonged period for total disintegration. The variations in degradation rates across several samples indicate that the proportions of banana peel, chitosan, and fish scales influence biodegradability.The elevated biodegradation rate of Sample 1 indicates that the amalgamation of banana peel starch, chitosan, and fish scales produces a bioplastic substance capable of efficiently decomposing in soil conditions. The inclusion of natural polymers in these components, coupled with their compatibility with microbial activity, facilitates an expedited degradation process. The decrease in Sample 1's weight to about fifty percent of its original mass highlights its appropriateness for applications where biodegradability is essential, such as single-use packaging or disposable products. Likewise, Sample 2 exhibited a significant weight loss %, substantiating the notion that bioplastics composed of substantial banana peel content and proportionate amounts of chitosan and fish scales can attain efficient breakdown. The moderate biodegradation rates noted in Samples 3, 4, and 6 indicate that optimizing the composition of these bioplastics may improve their breakdown capacity. These findings emphasize the necessity to refine bioplastic formulations to suit particular industrial applications that demand both durability and biodegradability.Conversely, Sample 5 demonstrated the minimal weight loss % among the evaluated samples, indicating that its composition confers more resistance to microbial and environmental

Table 3. Biodegradation rates of bioplastic samples in various environmental conditions.

Sample	Weight of Sample before Biodegradation Test	Weight of Sample after Biodegradation Test (g)	Weight Loss (%)
1	99.985	21.75	78.235
2	99.995	22.65	77.345
3	100	51.65	48.35
4	99.95	55.35	44.60
5	100	61.55	38.45
6	100	58.48	41.52

degradation processes. This observation indicates that the interaction of chitosan, banana peel starch, and fish scales in this particular ratio produces a denser matrix that impedes the biodegradation process. The longer stability of Sample 5 may be beneficial for applications necessitating prolonged utilization prior to breakdown, such as in durable packaging or biological uses. The variance in degradation rates among different formulations underscores the impact of compositional balance on bioplastic efficacy. The research highlights the necessity of modifying the proportions of raw materials to attain the optimal equilibrium of strength, functionality, and ecological sustainability. By adjusting the proportions of banana peel, chitosan, and fish scales, bioplastic compositions can be customized for various uses, from short-term biodegradable items to more resilient materials necessitating regulated degradation rates.These discoveries offer significant insights into the creation of sustainable substitutes for petroleum-derived polymers. The capacity to modify bioplastic formulations according to particular requirements increases their prospects for commercial success. Furthermore, the efficacy of Sample 1 in exhibiting significant biodegradability substantiates the viability of utilizing agricultural waste as a principal element in the manufacture of eco-friendly bioplastics. This method not only alleviates plastic pollution but also encourages waste valorization through the use of banana peels and fish scales—two abundant, renewable resources. The primary results of this investigation are illustrated in **Table 4**, highlighting the importance of material composition in influencing biodegradability rates. Subsequent study must concentrate on optimizing the formulation to improve mechanical capabilities while maintaining the degradation rate, thus providing a viable and sustainable substitute for traditional plastics.

Table 4. Summary of main results (% analysis).

Run	Component 1 A: Banana Peel (%)	Component 2 B: Fish Scale (%)	Component 3 C: Chitosan (%)	Response 1 Tensile Strength ($N\ m^{-2}$)	Response 2 Biodegradability (%)
1	0.5782	0.250	0.198	29.45	78.45
2	0.5655	0.355	0.149	27.65	75.55
3	0.650	0.355	0.155	31.45	49.55
4	0.650	0.249	0.150	25.75	45.75
5	0.650	0.255	0.250	24.55	39.55
6	0.550	0.355	0.250	33.55	45.65

Tensile strength refers to the maximum force a film can endure before breaking. It is measured as the force required to stretch each unit area of the film. Based on the results, Sample 6 exhibited the highest tensile strength at 35.55 N m^{-2}, while Sample 5 showed the lowest at 25.5 N m^{-2}. Other samples demonstrated tensile strength values ranging from 24.55 to 31.45 N m^{-2}.

The addition of plasticizers significantly influenced tensile strength. The tensile strength increased with a moderate amount of banana peel, as seen in Sample 1, which had a tensile strength of 33.45 N m^{-2} with 55.07 g of peel. Conversely, Sample 5, with 65 g of fish scales, exhibited a lower tensile strength of 26.56 N m^{-2}. Higher fish scale content generally increased tensile strength, while lower values reduced it.

Chitosan's effect on tensile strength was inconsistent, with some samples showing increased strength and others the opposite. This indicates that chitosan alone does not determine tensile strength. Overall, moderate levels of banana peels and fish scales yielded balanced tensile strength values, whereas increased flexibility due to excessive plasticizer addition reduced tensile strength by making the film softer and more pliable.

3.1. Results for Sample-1

The first 3D graph represents the results of the tensile strength of 3 components, using design expert software, as shown in **Figure 1**.

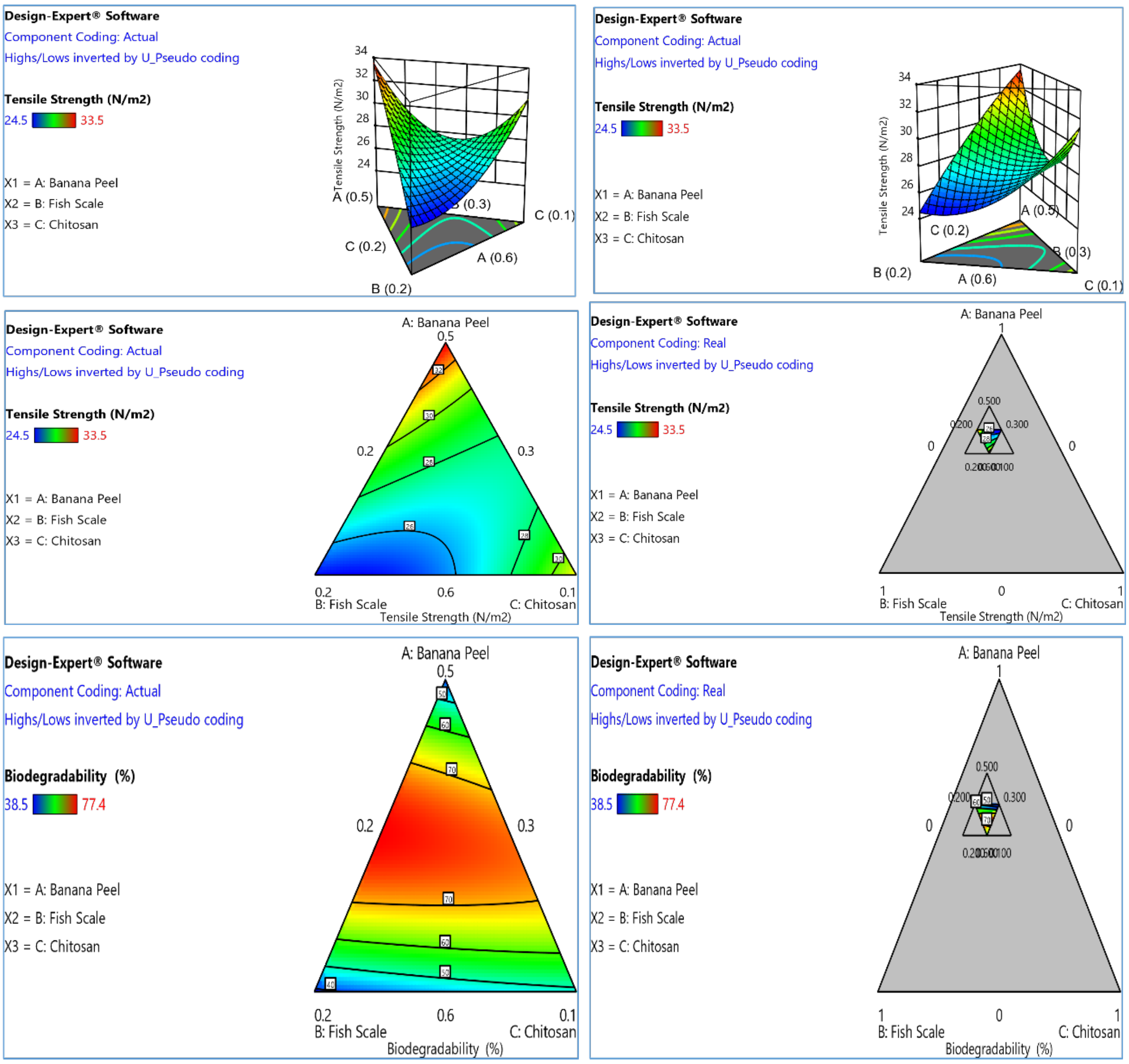

Figure 1. Three-dimensional graphs representing the variation in tensile strength.

Note: A: Banana peels; B: fish; C: Chitosan powder.

The graphs in **Figure 1** illustrate the effect of different compositions of banana peels (A), fish (B), and chitosan powder (C) on the tensile strength of the resulting material. The 3D response surface plots provide a visual representation of how tensile strength varies based on different combinations of these components.

- The first 3D plot demonstrates the interaction between the variables and highlights regions of high and low tensile strength.
- The corresponding contour plots offer a two-dimensional perspective of these variations, making it easier to identify optimal component ratios.

- The final triangular contour plot emphasizes the distribution of tensile strength across different composition levels, with color gradients indicating regions of maximum and minimum tensile strength.

Overall, these graphs help in identifying the ideal formulation that results in the highest tensile strength, useful for optimizing material properties in composite formulations are showed in **Table 5**.

Table 5 represents the lowest and highest values for each of the banana peels, fish peels, and chitosan, depending on the importance of the samples. **Table 6** shows the tensile strength details for the respective banana peel, fish scale, and chitosan.

The experimental constraints and limitations set for the composite material formulation, which includes banana peels, fish scales, and chitosan powder. The goal is to optimize the material properties by carefully selecting the component ranges. The proportion of banana peel is constrained between 0.52 and 0.65, ensuring sufficient fiber reinforcement while maintaining biodegradability. Fish scales are incorporated within 0.22 and 0.35, contributing to the material's mechanical strength. Chitosan, known for its binding properties, is included between 0.12 and 0.25, influencing both the tensile strength and biodegradability of the final composite. In terms of performance goals, the study aims to maximize tensile strength within a range of 24.5 to 33.5 MPa, ensuring that the material remains durable and structurally sound. Additionally, biodegradability is also prioritized, ranging from 38.25 to 77.5, indicating the potential for environmentally friendly degradation after use. Each factor is assigned equal weight and importance, demonstrating a balanced approach to optimizing the material rather than favoring one characteristic over another.

Table 6 evaluates four potential solutions based on their composition, tensile strength, biodegradability, and overall desirability. The optimization criteria in these plots are defined with the objective of attaining a goal desirability value of 0.810. The optimal composition to achieve this aim is 54.5 g of banana peel (0.545%), 27.5 g of fish scales (0.275%), and 20 g of chitosan powder (0.225%). This composition achieves a tensile strength of approximately 32.962 N m^{-2} and a biodegradability rate of about 75.057%. Among the four evaluated solutions, Solution 1 is selected as the optimal formulation, as it provides the best balance between mechanical strength and biodegradability. Other solutions demonstrate lower desirability due to trade-offs between these properties. Solution 2 exhibits slightly higher biodegradability (76.493) but at the cost of a reduced tensile strength of 28.562 MPa, leading to a lower desirability score of 0.760. Solutions 3 and 4 further decrease in performance, with tensile strength values of 28.339 MPa and 27.689 MPa, respectively, and biodegradability scores dropping to 65.659 and 62.510. As a result, their desirability indices are significantly lower (0.621 and 0.555), making them less favorable for practical applications.

The optimization procedure ensures that the error is minimized in the designated responses across the entire spectrum of input variables. The desirability function method was employed to balance the trade-off between maximizing tensile strength and achieving high biodegradability, ensuring that the resulting material meets practical application requirements. This optimization criterion is particularly relevant to Sample 1, which was chosen for its exceptional performance regarding strength and environmental compatibility.

The data indicate that the developed bioplastic preserves mechanical integrity while exhibiting an effective degradation rate, positioning it as a viable substitute for petroleum-derived plastics. The findings demonstrate that the suggested formulation is an efficient, sustainable, and biodegradable alternative appropriate for diverse industrial applications, such as packaging and molding. This study confirms that the selected component ratios effectively enhance the material's properties, making it suitable for applications requiring both durability and environmental responsibility.

4. Conclusions

The experimental investigation determined that the sample consisting of 55.35 g of banana peel, 20 g of chitosan, and 25.35 g of fish scales demonstrated the highest decomposition rate at 75.057%, with its weight reducing from 99.98 g to 22.5 g after burial, indicating effective biodegradation without environmentally harmful residues and within a faster timeframe. Upon withdrawal, this sample was observed to be lighter and less brittle, with fish scales and banana peels significantly influencing results more than chitosan. Higher fish scale content correlated with greater tensile strength, though moderate values for both components were optimal for stabil-

Table 5. Experimental constraints and limitations.

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Banana peel		0.52	0.65	1	1	3
B: Fish	is in range	0.22	0.35	1	1	3
C: Chitosan		0.12	0.25	1	1	3
Tensile strength	maximize	24.5	33.5	1	1	3
Biodegradability	maximize	38.25	77.5	1	1	3

Table 6. Evaluation of four potential solutions with the selected one highlighted.

#	Banana Peel	Fish Scale	Chitosan	Tensile Strength	Bio-Degradability	Desirability	
1	0.545	0.275	0.225	32.962	75.057	0.910	Selected
2	0.550	0.250	0.200	28.562	76.493	0.760	
3	0.525	0.300	0.175	28.339	65.659	0.621	
4	0.580	0.300	0.125	27.689	62.510	0.555	

ity. The predicted and actual tensile strength and degradability values for this sample are aligned closely, confirming its suitability and accuracy. Optimization using Design Expert software identified a desirability of 0.955, achievable with 55.38 g banana peel, 27.63 g fish scales, and 20 g chitosan powder, resulting in a tensile strength of 35.97 N m^{-2} and biodegradability of approximately 76.05%.

Author Contributions

N.R.L.: Conceptualized the study, supervised the experimental work, and contributed to the manuscript's drafting and final approval. L.J.J.: Conducted literature review and data analysis, focusing on the environmental implications of biodegradable plastics, and contributed to the manuscript preparation. A.R.K.: Led the experimental setup and material formulation, ensuring accurate implementation of the Design Expert software for optimization. C.V.K.: Provided technical support for tensile strength testing and biodegradability analysis and assisted in refining the experimental procedures. N.R.B.: Conducted the sourcing and preparation of raw materials, including banana peel, fish scales, and chitosan powder, and managed laboratory logistics. D.D.: Assisted in analyzing the results and contributed to discussions regarding the industrial applications of the bioplastic films. G.K.: Supported the project by reviewing experimental results and contributing insights into the potential applications of bioplastics in packaging and molding. R.N.: Coordinated the overall project, provided critical revisions to the manuscript, and handled the communication with the journal as the corresponding author.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. All relevant data are included in the manuscript and its supplementary materials.

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Conflicts of Interest

The authors declare no conflict of interest.

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