

Development of BioFlex EcoPlast™: A High-Strength Biodegradable Composite Plastic from Banana Peel, Sugarcane Bagasse, Banana Fibre, and Treated Textile Dye Wastewater

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Abstract

The increasing accumulation of petroleum-based plastic waste, together with the growing generation of agricultural residues and industrial wastewater, has created a need for integrated and sustainable waste-valorization strategies. Conventional plastics offer excellent durability and versatility but are highly persistent in the environment, while many existing bioplastics suffer from inadequate mechanical strength, moisture sensitivity, and limited thermal stability. The present study proposes BioFlex EcoPlast™: a High-Strength Biodegradable Composite Plastic from Banana Peel, Sugarcane Bagasse, Banana Fibre, and Treated Textile Dye Wastewater as a conceptual multi-waste material system developed through secondary research and systematic literature synthesis. Published studies were comparatively analyzed to evaluate banana-peel bioplastics, natural-fibre reinforcement, sugarcane-bagasse composites, banana-fibre applications, textile wastewater treatment, wastewater reuse, and circular-economy approaches. The synthesis indicates that banana peel can serve as a biodegradable biomass matrix but generally requires reinforcement to overcome limitations in mechanical performance. Sugarcane bagasse can potentially contribute stiffness and structural stability, while banana fibre provides a cellulose-rich reinforcing phase capable of supporting tensile load transfer. Plasticizer incorporation is considered necessary to improve flexibility and processability, although excessive plasticizer content may reduce strength and increase moisture sensitivity. Textile dye wastewater presents a distinct challenge; therefore, the proposed framework considers only appropriately treated wastewater as a controlled process-resource component, subject to contaminant removal, chemical characterization, toxicity assessment, and safety validation. Based on the reviewed evidence, BioFlex EcoPlast™ integrates these complementary functions within a circular-economy pathway that connects agricultural-residue valorization, industrial wastewater resource recovery, biodegradable composite development, and appropriate end-of-life management. The study identifies a significant research gap in the integrated utilization of banana peel, sugarcane

bagasse, banana fibre, and treated textile wastewater within a single biodegradable composite framework. Importantly, BioFlex EcoPlast™ is a literature-derived conceptual model and has not yet been experimentally validated. Future research should therefore focus on formulation optimization, mechanical and thermal characterization, water-resistance testing, biodegradation assessment, wastewater safety, life-cycle assessment, techno-economic analysis, and pilot-scale development. The proposed framework provides a foundation for future experimental investigation into high-performance, waste-derived biodegradable composite plastics.

Keywords: BioFlex EcoPlast™; biodegradable composites; banana peel bioplastics; sugarcane bagasse; banana fibre reinforcement; textile wastewater reuse; circular economy; waste valorization.

Introduction

1.1 Background of Plastic Pollution

The rapid growth of plastic production and consumption has created a major global environmental challenge. Petroleum-derived plastics are widely used because of their low cost, light weight, durability, chemical resistance, and versatility. However, these same properties make conventional plastics highly persistent after disposal. Large quantities of plastic waste accumulate in landfills, terrestrial environments, rivers, and marine ecosystems, where gradual fragmentation can contribute to the formation of microplastics. Conventional management approaches, including landfilling, incineration, and recycling, can reduce some waste burdens but cannot completely address the increasing volume and long-term persistence of plastic waste. Consequently, research is increasingly directed toward renewable and biodegradable alternatives that can reduce dependence on fossil-derived polymers while maintaining acceptable material performance.

1.2 Rise of Bioplastics

The development of bioplastics and biodegradable biocomposites has emerged as an important research direction for addressing the environmental limitations of conventional plastics. Bioplastics can be produced from renewable resources such as starch, cellulose, agricultural residues, and other biomass materials. Their major advantages include renewable feedstock availability, potential biodegradability, and opportunities for agricultural-waste valorization. However, the literature indicates that replacing conventional plastics is technically challenging because many biomass-based polymers exhibit relatively low tensile strength, poor moisture resistance, brittleness, and limited thermal stability. Therefore, current research increasingly focuses on fibre-reinforced biocomposites, where a biodegradable

matrix is combined with natural fibres or cellulose-rich residues to achieve a more balanced combination of strength, flexibility, stability, and biodegradability.

1.3 Banana Peel as a Reported Biopolymer Source

Agricultural residues represent particularly attractive feedstocks because they can simultaneously address waste-management and material-resource challenges. Banana peel contains several structurally important constituents, including starch, cellulose, hemicellulose, lignin, and pectin, making it a promising biomass source for biodegradable material development. Previous research has demonstrated the feasibility of converting banana-peel flour into bioplastic films using plasticizers such as glycerol and sorbitol. The attached banana-peel study, for example, investigated banana-peel flour with cellulose reinforcement and different plasticizer formulations and evaluated tensile properties, thickness, water-vapor permeability, breaking behavior, and biodegradation. However, the reported tensile performance also demonstrates an important limitation: banana-peel-based materials alone may not provide sufficient mechanical strength for demanding plastic applications. Therefore, additional reinforcement is required when higher structural performance is targeted.

1.4 Sugarcane Bagasse in Composite Materials

Sugarcane bagasse is another abundant agricultural residue with considerable potential for biodegradable composite development. It contains cellulose, hemicellulose, and lignin and can be processed into fibres or cellulose-rich reinforcing materials. The literature indicates that bagasse-based reinforcement can contribute to stiffness, structural stability, and improved mechanical performance. Pretreatment can further improve fibre accessibility and interfacial interaction with polymer matrices. However, because lignocellulosic fibres are naturally hydrophilic, their compatibility with some polymer matrices can be limited. Fibre treatment, loading level, dispersion, and matrix–fibre adhesion therefore become important factors in composite design.

1.5 Banana Fibre as Reinforcement Material

Banana fibre provides another promising reinforcement because of its cellulose-rich structure and reported mechanical potential. Natural banana fibres have been investigated as reinforcement for polymer composites, with research indicating their potential contribution to tensile strength, stiffness, and structural stability. The combination of banana peel and banana

fibre is particularly attractive from a waste-valorization perspective because both materials originate from banana production but can perform different functions within the composite. Banana peel can provide the biodegradable matrix, while banana fibre can contribute structural reinforcement. Nevertheless, fibre length, surface treatment, loading concentration, orientation, dispersion, and fibre–matrix compatibility must be optimized to achieve effective reinforcement.

1.6 Textile Dye Wastewater: Environmental Concern

Alongside agricultural residues, textile dye wastewater represents an important industrial waste stream. Textile processing can generate wastewater containing dyes, suspended solids, salts, organic compounds, and, depending on the process, potentially hazardous inorganic contaminants. Inadequately treated discharge can adversely affect aquatic ecosystems and water quality. Consequently, research has focused on wastewater-treatment technologies including coagulation–flocculation, adsorption, membrane separation, biological treatment, electrochemical processes, and advanced oxidation. Although treatment can reduce pollutant concentrations, the resulting water remains a potential resource that requires appropriate quality assessment before reuse.

1.7 Concept of Wastewater Reuse in Materials

The transition from wastewater disposal toward resource recovery and controlled reuse is increasingly consistent with circular-economy principles. Treated industrial wastewater can potentially be reused in selected non-potable applications, thereby reducing freshwater demand and improving resource efficiency. However, the literature reviewed for the present study provides considerably stronger evidence for textile wastewater treatment and industrial reuse than for its direct use in biodegradable composite-material synthesis. Therefore, the proposed use of treated textile dye wastewater in BioFlex EcoPlast™ should be regarded as an emerging research hypothesis, requiring contaminant analysis, toxicity assessment, compatibility studies, and validation before practical implementation.

1.8 Research Gap

The literature synthesis reveals that research on the individual components of the proposed system is considerably more developed than research on their integrated utilization. Banana-peel studies have primarily focused on biodegradable film formation and formulation

optimization, while sugarcane-bagasse and banana-fibre research has concentrated on natural-fibre reinforcement. Textile wastewater research has predominantly addressed pollutant removal and water reuse rather than composite-material development. Thus, there is limited evidence for a unified system combining banana peel, sugarcane bagasse, banana fibre, and appropriately treated textile dye wastewater within one biodegradable composite framework. The available literature also lacks sufficient integrated circular-economy models linking agricultural residue recovery, industrial wastewater treatment, composite production, and end-of-life management.

1.9 Novelty of the Study

Against this background, the present secondary study proposes BioFlex EcoPlast™: a High-Strength Biodegradable Composite Plastic from Banana Peel, Sugarcane Bagasse, Banana Fibre, and Treated Textile Dye Wastewater. The proposed conceptual model assigns different functional roles to the four resource streams: banana peel as the biodegradable matrix/feedstock, sugarcane bagasse as a structural filler/reinforcement, banana fibre as a reinforcing phase, and appropriately treated textile dye wastewater as a controlled process-resource component. This integrated approach seeks to connect agricultural-waste valorization with industrial wastewater resource recovery within a circular-economy framework.

The novelty of the study therefore lies not in claiming that each individual material is new, but in proposing their integrated multi-waste utilization pathway and identifying the scientific requirements for its future validation. The model provides a foundation for subsequent experimental studies involving formulation optimization, mechanical and thermal characterization, water-resistance testing, biodegradation assessment, wastewater safety evaluation, life-cycle assessment, and techno-economic analysis. Importantly, because the present investigation is a secondary study, BioFlex EcoPlast™ is proposed as a conceptual research model rather than an experimentally validated commercial material. This distinction strengthens the scientific credibility of the research while establishing a clear pathway for future experimental development.

2 Aim and Objectives

Aim

To conduct a secondary research-based systematic review and conceptual synthesis on the development of BioFlex EcoPlast™, a multi-waste biodegradable composite system derived from agricultural residues and treated textile wastewater.

Objectives

To review literature on banana peel-based bioplastics and their material properties.

To analyze sugarcane bagasse as a reinforcement material in biocomposites.

To evaluate banana fibre as a natural strengthening agent.

To examine treatment methods and reuse potential of textile dye wastewater.

To synthesize existing findings into a conceptual BioFlex EcoPlast™ framework.

To identify key factors influencing mechanical, thermal, and biodegradation performance.

To propose a circular economy model integrating agricultural and industrial waste streams.

3. Research Questions

The present study addresses the following key research questions:

- 1.What are the reported properties of banana-peel-based bioplastics?
- 2.How does sugarcane bagasse improve the mechanical properties of biocomposites?
- 3.What role does banana fibre play in improving composite strength and stability?
- 4.Which treatment methods support the reuse of textile dye wastewater?
- 5.Can banana peel, bagasse, banana fibre, and treated wastewater be integrated into one composite system?
- 6.What are the major limitations of existing biodegradable plastics?
- 7.How can these waste materials support a circular-economy and waste-valorization model?

4. Hypotheses (Conceptual)

The following conceptual hypotheses are proposed based on the findings of the reviewed literature:

□ **H1:** Natural-fibre reinforcement is expected to improve the mechanical properties of banana-peel-based bioplastics.

□ **H2:** Sugarcane bagasse is expected to enhance stiffness and structural stability of the biodegradable composite.

□**H3:** Banana fibre is expected to improve tensile strength and reduce brittleness through better load transfer.

□**H4:** Appropriately treated textile dye wastewater may be conceptually used as a controlled process medium, subject to safety and contaminant assessment.

□**H5:** Integrating multiple agricultural and industrial waste streams is expected to provide greater waste-valorization and circular-economy potential than single-source bioplastic systems.

5. Literature Review

5.1 Plastic Pollution and Sustainable Waste Management

The increasing dependence on petroleum-derived plastics has generated persistent environmental challenges because conventional polymers generally exhibit high durability and low biodegradability. Plastic waste can accumulate in landfills and aquatic environments, while inadequate disposal and thermal treatment may generate additional environmental burdens. Consequently, research has increasingly shifted toward renewable, biodegradable, and waste-derived materials that can replace selected conventional plastic applications. The attached literature identifies bioplastics as an important alternative because they can be produced from renewable biomass and, depending on their composition, can offer improved end-of-life biodegradability.

However, biodegradability alone does not guarantee a technically viable plastic substitute. A sustainable material must also provide adequate tensile strength, flexibility, moisture resistance, thermal stability, processability, and economic feasibility. Therefore, recent research increasingly focuses on biocomposites, in which a biodegradable matrix is reinforced with natural fibres or cellulose-rich residues. This approach is particularly relevant for agricultural waste because it converts low-value biomass into functional materials while reducing dependence on virgin polymer resources.

5.2 Banana Peel-Based Bioplastics

Banana peel has attracted considerable attention as a potential feedstock for biodegradable plastics because it contains starch, cellulose, hemicellulose, lignin, pectin, and other organic components. The attached research confirms that banana-processing residues contain

structurally useful compounds and can be converted into bioplastic materials through drying, grinding, plasticization, and film formation.

Alcivar-Gavilanes et al. (2022) demonstrated the development of banana-peel-based bioplastic formulations using banana-peel flour and cellulose, with glycerol and sorbitol investigated as plasticizers. Their optimized formulation achieved a tensile strength of approximately 2.40 MPa, demonstrating the feasibility of banana peel as a bioplastic feedstock while also indicating the mechanical limitations of unreinforced or lightly reinforced systems. The study further showed that cellulose addition and plasticizer type influenced water-vapor permeability, tensile behavior, and breaking characteristics.

These findings suggest that banana peel can provide the biodegradable matrix component of BioFlex EcoPlast™, but additional reinforcement is necessary if higher mechanical performance is targeted.

5.3 Plasticizer Effects on Bioplastic Performance

Plasticizers such as glycerol and sorbitol are commonly used to increase flexibility and reduce brittleness in starch- and biomass-based films. Their action is generally associated with weakening intermolecular interactions and increasing polymer-chain mobility. However, excessive plasticizer concentration can decrease tensile strength and increase moisture sensitivity.

The attached banana-peel study found significant effects of plasticizer type on tensile strength, breaking behavior, and water-vapor permeability, demonstrating that formulation optimization is essential rather than simply increasing plasticizer content. Therefore, BioFlex EcoPlast™ should be conceptualized as a balanced matrix–plasticizer–fibre system, where flexibility and strength must be optimized simultaneously.

5.4 Natural Fibre Reinforcement

Natural cellulose fibres provide an important strategy for overcoming the mechanical limitations of starch- and peel-based bioplastics. Their reinforcing effect is associated with fibre stiffness, cellulose structure, and load transfer between the matrix and reinforcement. However, natural fibres are hydrophilic, whereas some polymer matrices are comparatively less polar, creating compatibility problems. Fibre surface treatments, particularly controlled alkali treatment, are therefore frequently investigated to remove portions of hemicellulose, lignin, waxes, and surface impurities and improve interfacial bonding.

Recent reviews of natural-fibre composites emphasize that reinforcement performance depends not only on fibre type but also on fibre treatment, loading, orientation, dispersion, and matrix compatibility. Thus, BioFlex EcoPlast™ should not simply add fibres in high quantities; the literature indicates that an optimum reinforcement level is necessary to avoid fibre agglomeration and loss of flexibility.

5.5 Sugarcane Bagasse as a Composite Reinforcement

Sugarcane bagasse is an abundant agro-industrial residue containing cellulose, hemicellulose, and lignin. Recent reviews identify bagasse as a promising feedstock for fibres, cellulose, nanocellulose, and biodegradable composite materials. Pretreatment can improve cellulose accessibility and consequently its reinforcement potential.

Research reviews further indicate that chemical treatment of bagasse fibres can influence their mechanical performance by improving fibre–matrix interaction. This makes bagasse particularly attractive for BioFlex EcoPlast™ because it can perform both a waste-valorization and structural-reinforcement function. Nevertheless, excessive fibre loading or poor dispersion may negatively influence composite uniformity and flexibility.

5.6 Banana Fibre Reinforcement

Banana fibre is another cellulose-rich agricultural residue with demonstrated potential as a reinforcement for polymer composites. Reviews of banana-fibre-reinforced polymers report considerable interest in their mechanical properties and potential for replacing conventional reinforcement materials. Banana fibre is particularly relevant to the proposed composite because it originates from the same agricultural system as banana peel, allowing two residues from banana production to be integrated into one material platform.

The combination of banana peel as a biodegradable matrix with banana fibre as reinforcement is therefore theoretically complementary: the peel contributes the polymer-forming biomass fraction, while the fibre contributes structural strength. However, the literature also suggests that fibre treatment, dispersion, fibre length, and matrix compatibility strongly influence final performance.

5.7 Textile Dye Wastewater Treatment

Textile dye wastewater represents a different category of waste because it contains dissolved dyes and other contaminants that can pose environmental risks if inadequately treated.

Conventional and advanced treatment approaches include coagulation–flocculation, adsorption, membrane separation, biological processes, electrochemical treatment, and advanced oxidation. The selection of treatment depends on wastewater composition, dye chemistry, pollutant concentration, treatment cost, and intended reuse.

For BioFlex EcoPlast™, this distinction is critical: treated textile wastewater should not be considered an ordinary biomass ingredient. Its potential use must depend on demonstrated removal of relevant contaminants and appropriate assessment of residual dye and other pollutants. Consequently, the proposed framework should treat wastewater purification as a prerequisite for any material-reuse pathway.

5.8 Wastewater Reuse and Circular Economy

Industrial wastewater reuse is increasingly associated with circular-economy approaches because it can reduce freshwater demand and transform wastewater from a disposal problem into a recoverable resource. Recent textile-sector reviews emphasize the importance of circular strategies, resource efficiency, and environmental assessment in reducing the impacts of textile production.

Nevertheless, the literature reviewed for this study provides much stronger evidence for textile wastewater treatment and industrial reuse than for direct incorporation of treated textile wastewater into biodegradable plastics. Therefore, the proposed use of treated wastewater in BioFlex EcoPlast™ should be presented as a conceptual research opportunity rather than an established technology.

5.9 Integrated Research Gap

The reviewed literature demonstrates substantial progress in banana-peel bioplastics, natural-fibre reinforcement, sugarcane-bagasse composites, and textile wastewater treatment, but these research streams remain largely separate. Banana-peel studies generally focus on improving film formation and mechanical properties; bagasse and banana-fibre research focuses primarily on reinforcement; and textile wastewater research focuses predominantly on pollutant removal and water reuse.

The major research gap is therefore the absence of a well-established multi-waste integration framework connecting banana peel, sugarcane bagasse, banana fibre, and treated textile dye wastewater within a single biodegradable composite system. BioFlex EcoPlast™ addresses this conceptual gap by proposing a circular material pathway in which agricultural residues provide matrix and reinforcement components while appropriately treated industrial

wastewater is considered as a controlled process resource. The framework provides a basis for future experimental validation, optimization, environmental safety assessment, life-cycle analysis, and scale-up.

6.1 Research Design

The present study adopts a secondary research design based on a systematic literature review, comparative evidence synthesis, thematic analysis, and conceptual framework development. No new laboratory experiments are conducted in the present study. Instead, previously published scientific evidence is systematically examined to understand the potential of banana peel, sugarcane bagasse, banana fibre, and treated textile dye wastewater as components of a sustainable biodegradable composite system.

The research design consists of four interconnected stages:

Literature identification → Evidence screening → Comparative synthesis → BioFlex EcoPlast™ conceptual framework

The first stage identifies published research concerning biodegradable plastics, banana-peel bioplastics, cellulose-based composites, sugarcane bagasse, banana fibre, textile wastewater treatment, wastewater reuse, and circular-economy material systems. The second stage evaluates the relevance and quality of retrieved studies using predefined inclusion and exclusion criteria. The third stage extracts and compares information concerning material composition, processing approaches, tensile strength, flexibility, water resistance, thermal stability, biodegradability, and environmental performance. Finally, the evidence is synthesized into the proposed BioFlex EcoPlast™ model.

This design is appropriate because the individual components of the proposed composite have already been investigated in different research areas, whereas their combined application remains comparatively underexplored. The attached banana-peel study, for example, demonstrates that banana-derived materials can be evaluated through physical, mechanical, water-vapor, and biodegradation parameters.

6.2 Data Sources

Scientific literature should be collected from multiple academic databases to improve coverage and reduce dependence on a single source.

Primary bibliographic databases

The proposed databases are:

- ☐ Scopus
- ☐ Web of Science
- ☐ Google Scholar

Additional sources may include publisher databases and institutional repositories when full-text access is required.

The review period should primarily cover **2010–2025**, with greater emphasis placed on recent studies published between **2020** and **2025** to capture developments in biodegradable composites, natural-fibre reinforcement, textile wastewater treatment, and circular economy.

6.3 Analysis Method

The collected literature was analyzed using three complementary approaches: thematic analysis, comparative synthesis, and material-property mapping. These methods were used to identify common findings, research limitations, and potential opportunities for developing the proposed BioFlex EcoPlast™ composite.

6.3.1 Thematic Analysis

The selected studies were organized into ten major themes related to the development of BioFlex EcoPlast™. These included plastic pollution and bioplastic development, banana peel as a polymer-forming biomass, plasticizer effects, natural-fibre reinforcement, sugarcane bagasse composites, banana fibre composites, textile wastewater treatment, wastewater reuse, circular economy, and multi-waste material development. Thematic analysis was used to identify recurring findings across the literature, particularly regarding the ability of agricultural residues to provide biodegradable matrix or reinforcement components, the influence of plasticizers and natural fibres on material performance, and the potential for treated industrial wastewater to support resource-recovery approaches. The analysis also identified limitations reported in previous studies, including low mechanical strength, moisture sensitivity, fibre–matrix compatibility, and insufficient integration of multiple waste streams. These recurring findings were subsequently used to identify research opportunities and establish the conceptual basis for the proposed BioFlex EcoPlast™ system. The attached literature similarly demonstrates the importance of examining formulation, cellulose reinforcement, plasticizer effects, water-vapor behavior, tensile performance, and biodegradability when evaluating banana-peel-based bioplastics.

6.3.2 Comparative Synthesis

The selected studies were comparatively analyzed based on material composition, processing technique, reinforcement level, tensile strength, flexibility, water resistance, thermal stability, biodegradation, and environmental benefits. This comparison helped identify how differences in biomass type, fibre concentration, plasticizer content, and processing conditions influence the performance of biodegradable composite materials. Particular attention was given to the

relationship between reinforcement and mechanical properties, as well as the balance between strength, flexibility, moisture resistance, and biodegradability. The attached banana-peel research demonstrates the importance of formulation-level comparison, as different formulations showed differences in thickness, water-vapor permeability, tensile force, and breaking time. Therefore, comparative synthesis was used to identify the most promising material combinations and processing approaches for the proposed BioFlex EcoPlast™ system.

6.3.3 Material Property Mapping

A material-property matrix was developed to establish the functional contribution of each component to the proposed BioFlex EcoPlast™ composite. Banana peel was considered the primary biodegradable matrix/feedstock, providing the biomass fraction for composite formation. Sugarcane bagasse was considered a filler or reinforcing component that can contribute to stiffness and structural stability, while banana fibre was identified as a natural reinforcement with potential to improve tensile strength and load transfer within the matrix. Plasticizer was considered a flexibility modifier, supporting processability and reducing brittleness. Treated textile wastewater was considered a controlled process resource, representing the proposed water-resource recovery component; however, its suitability requires adequate treatment and safety assessment. Finally, the combined system represents the proposed BioFlex EcoPlast™ composite, in which the different components are intended to provide a balance between mechanical performance, flexibility, biodegradability, and waste valorization.

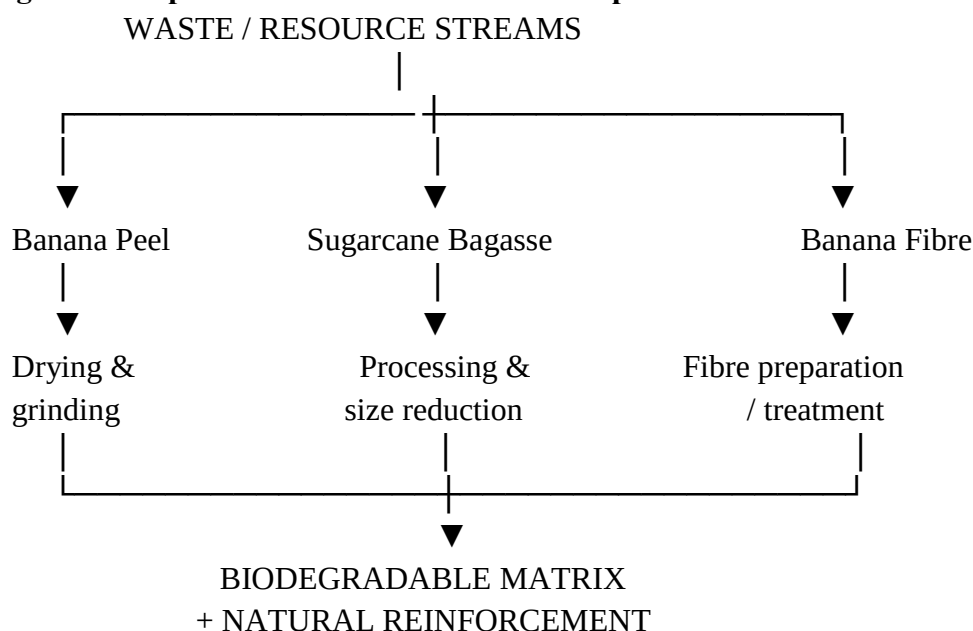
Component	Main Function	Expected Contribution
Banana peel	Matrix/feedstock	Biodegradable polymer-forming fraction
Sugarcane bagasse	Filler/reinforcement	Stiffness and structural stability
Banana fibre	Reinforcement	Tensile strength and load transfer
Plasticizer	Flexibility modifier	Processability and flexibility
Treated textile wastewater	Controlled process resource	Water/resource recovery
Combined system	Composite	Balanced performance and waste valorization

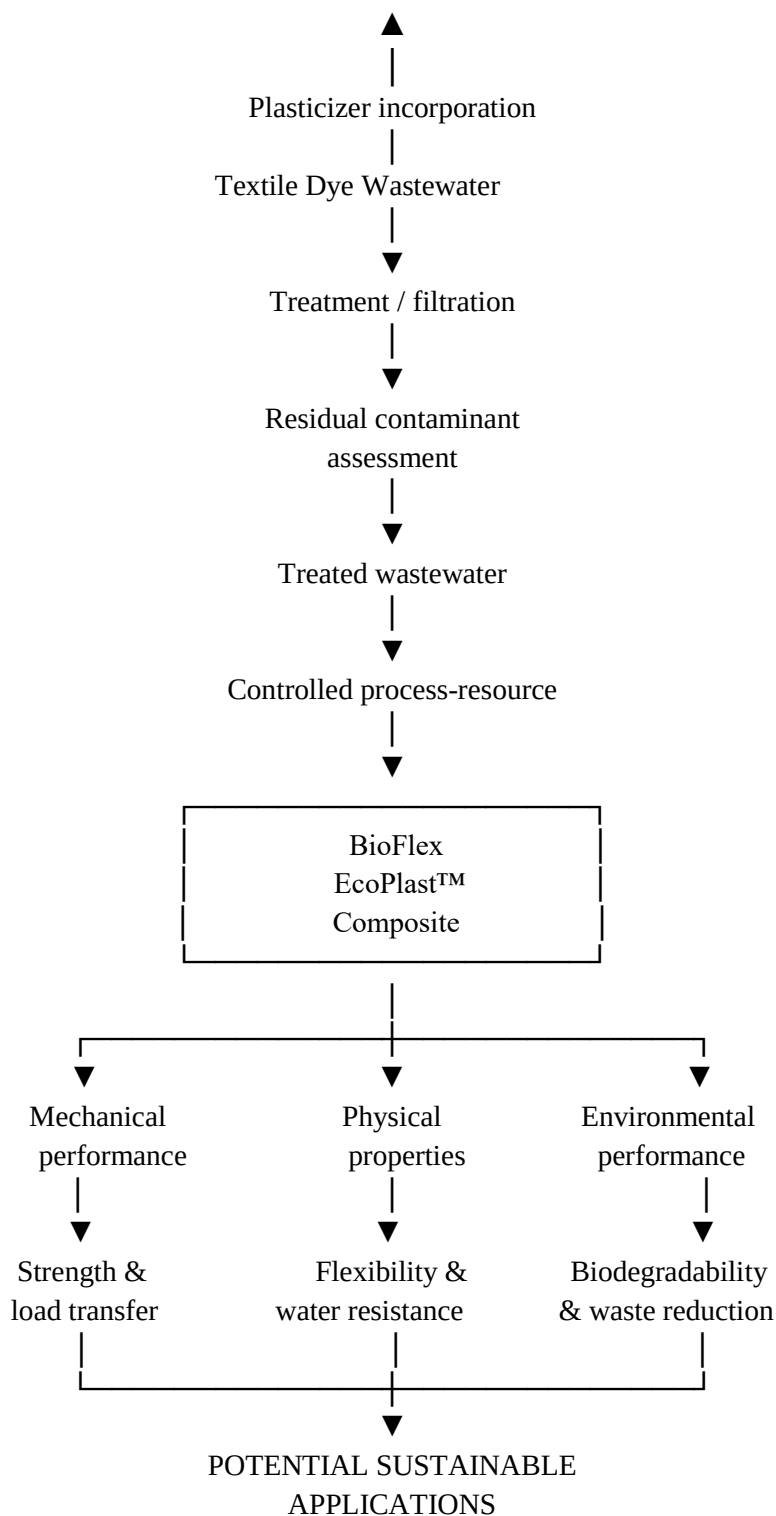
6.4 Conceptual Framework Development

The BioFlex EcoPlast™ conceptual framework was developed by integrating findings from the reviewed literature on banana-peel bioplastics, lignocellulosic reinforcement, natural fibres, textile wastewater treatment, and circular-economy approaches. The purpose of the framework is to explain how four different waste/resource streams—banana peel, sugarcane bagasse, banana fibre, and treated textile dye wastewater—can theoretically be integrated into a single biodegradable composite material.

The framework is based on the principle that each component performs a different function. Banana peel is proposed as the primary biodegradable matrix/feedstock, while sugarcane bagasse and banana fibre provide potential structural reinforcement. A plasticizer is incorporated to improve flexibility and processability. Treated textile dye wastewater is considered a controlled process-resource component, rather than a structural ingredient. Its inclusion is subject to adequate treatment and confirmation that residual contaminants are within acceptable limits. The attached banana-peel research supports the use of banana-derived materials and cellulose reinforcement for developing biodegradable films and demonstrates that formulation differences can influence tensile properties, water-vapor permeability, thickness, and breaking behavior.

Figure 1. Proposed BioFlex EcoPlast™ Conceptual Framework





The first stage of the framework involves the collection and valorization of agricultural and industrial waste. Banana peel is proposed as the principal biomass feedstock because banana-peel-based materials have already demonstrated potential for biodegradable film formation. The attached research used banana-peel flour together with cellulose and plasticizers and evaluated the resulting materials for mechanical and barrier properties.

Sugarcane bagasse and **banana fibre** are incorporated as natural reinforcement components. Their proposed role is to improve structural stability and load transfer within the banana-peel-based matrix. The literature suggests that natural-fibre reinforcement can help overcome the relatively low mechanical strength frequently associated with unreinforced biomass-based films.

A **plasticizer** is incorporated to improve flexibility and reduce brittleness. However, its concentration must be optimized because increasing flexibility may occur at the expense of tensile strength and moisture resistance. The attached study demonstrated that plasticizer selection and formulation affected tensile behavior and water-vapor permeability.

The fourth waste stream is **textile dye wastewater**. In the proposed framework, wastewater is first subjected to appropriate treatment and contaminant assessment. Only after adequate treatment is it considered as a controlled process resource. This is an important distinction because the present secondary study does **not experimentally establish that treated textile wastewater is safe or suitable for direct incorporation**.

The final stage is the formation of BioFlex EcoPlast™, whose expected performance is assessed conceptually through four major dimensions: mechanical strength, flexibility/water resistance, thermal stability, and biodegradability.

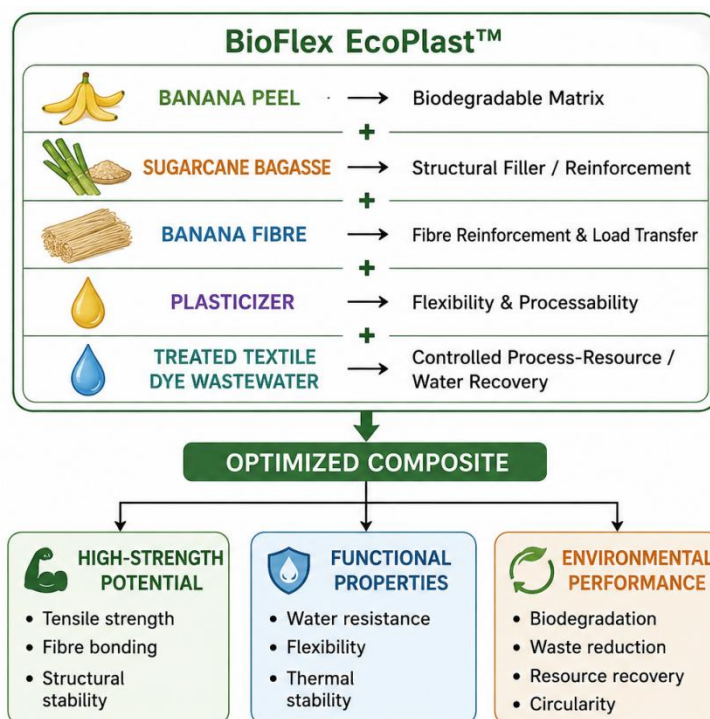


Figure 2 presents the functional role of each component within the proposed BioFlex EcoPlast™ system. Rather than treating all four wastes as equivalent ingredients, the framework assigns a specific purpose to each material. Banana peel provides the principal biodegradable biomass matrix, while sugarcane bagasse and banana fibre are expected to provide reinforcement. Plasticizer is used to modify flexibility and processability, whereas treated textile wastewater represents the proposed resource-recovery component.

The combination is intended to overcome some of the limitations identified in the existing banana-peel bioplastic literature. For example, the attached study reported that banana-peel formulations can be biodegradable but that formulation composition substantially affects tensile force, breaking behavior, thickness, and water-vapor permeability. Thus, the BioFlex EcoPlast™ framework emphasizes optimization rather than simply maximizing the amount of any one component.

6.5 Expected Performance Dimensions

The conceptual framework proposes five principal performance dimensions:

1. Mechanical Performance

Sugarcane bagasse and banana fibre are expected to contribute to improved structural stability and tensile load transfer. However, excessive reinforcement may produce poor dispersion or reduce flexibility. Therefore, the literature supports the need to identify an optimum

composition rather than assuming that higher fibre concentration will always improve performance.

2. Flexibility

The plasticizer is expected to increase chain mobility and reduce brittleness. However, excessive plasticizer may reduce tensile strength and increase moisture sensitivity. Consequently, flexibility and strength should be treated as interconnected properties.

3. Water Resistance

Banana peel and natural fibres contain hydrophilic components, which can increase water absorption. Therefore, water absorption, water solubility, and water-vapor permeability are important criteria for evaluating the proposed material. The attached research confirms the relevance of water-vapor permeability in assessing banana-peel bioplastic formulations.

4. Thermal Stability

The proposed composite should be evaluated against the thermal behavior reported for comparable biomass-based materials. Thermal stability will determine the potential processing conditions and practical applications of the material.

5. Biodegradability

The biodegradable nature of the biomass matrix is a central objective of BioFlex EcoPlast™. However, biodegradation should be assessed using standardized conditions because degradation rates reported in different studies may not be directly comparable.

6.5.2 Circular-Economy Interpretation

The conceptual framework also represents a transition from a **linear waste-management model to a circular resource model**:

Agricultural production → agricultural waste → material feedstock

Textile production → dye wastewater → treatment → controlled resource recovery

Waste resources → BioFlex EcoPlast™ → useful product → appropriate end-of-life management

Thus, the proposed system simultaneously addresses **agricultural waste generation, textile wastewater management, and petroleum-plastic dependence**.

6.6 Methodological Limitations

The present study has several methodological limitations that should be considered when interpreting the proposed BioFlex EcoPlast™ framework. First, the study is based entirely on secondary research and conceptual synthesis; therefore, no laboratory-scale fabrication or experimental testing of the proposed composite was performed. The expected contributions of banana peel, sugarcane bagasse, banana fibre, plasticizer, and treated textile dye wastewater are derived from previously published research and should not be interpreted as experimentally validated properties of BioFlex EcoPlast™.

Second, direct comparison of reported material properties is limited by differences among previous studies in raw-material composition, fibre size, pretreatment methods, plasticizer concentration, processing conditions, specimen dimensions, testing standards, and experimental environments. Consequently, reported tensile strength, flexibility, water resistance, thermal stability, and biodegradation values cannot always be compared directly across studies.

Third, the chemical composition of banana peel, sugarcane bagasse, and banana fibre can vary according to cultivar, maturity, geographical origin, agricultural conditions, and pretreatment. Such variation may influence matrix formation, fibre–matrix compatibility, mechanical strength, and biodegradation of the proposed composite. Similarly, the performance of natural-fibre reinforcement depends on fibre loading, dispersion, orientation, surface treatment, and interfacial bonding.

A particularly important limitation concerns treated textile dye wastewater. The reviewed literature provides substantial information on textile wastewater treatment and resource recovery, but comparatively limited evidence exists regarding its direct use in biodegradable composite-plastic development. Therefore, its proposed role in BioFlex EcoPlast™ remains conceptual rather than experimentally established. Adequate treatment, residual dye removal, chemical characterization, toxicity assessment, and leaching studies would be necessary before considering such wastewater suitable for incorporation into a plastic-processing system.

Another limitation is that the proposed high-strength characteristic has not yet been experimentally demonstrated. Although the literature indicates that natural fibres and lignocellulosic materials can improve mechanical properties, the actual strength of BioFlex

EcoPlast™ will depend on the optimum ratio of banana peel, bagasse, banana fibre, plasticizer, and other processing variables. The attached banana-peel research itself demonstrates that changes in formulation can produce differences in tensile performance, thickness, water-vapor permeability, and breaking behavior.

The study also does not conduct a life-cycle assessment (LCA), techno-economic analysis, or industrial-scale feasibility assessment. Therefore, claims concerning carbon reduction, economic advantage, energy savings, or superiority over conventional plastics should be considered potential benefits rather than confirmed outcomes. Similarly, biodegradability should not be assumed solely from the presence of natural materials; the final composite must be tested under standardized biodegradation or composting conditions because plasticizers, fibre treatments, processing additives, and residual wastewater constituents may influence degradation behavior.

Finally, the proposed BioFlex EcoPlast™ framework represents a research hypothesis and literature-derived conceptual model. Its actual feasibility requires future experimental investigation involving formulation optimization, tensile and flexural testing, water absorption and barrier analysis, FTIR/SEM characterization, thermal analysis (TGA/DSC), biodegradation testing, and safety assessment of the treated wastewater component. Future research should also investigate different component ratios and processing conditions to determine whether the proposed multi-waste system can achieve a scientifically validated balance between mechanical strength, flexibility, water resistance, thermal stability, biodegradability, and environmental safety.

6.6 Circular Economy Modeling

The circular economy model for **BioFlex EcoPlast™** proposes converting agricultural and industrial wastes into useful material resources. **Banana peel** is considered the biodegradable matrix, while sugarcane bagasse and banana fibre serve as natural reinforcement to improve structural properties. A plasticizer is proposed to enhance flexibility and processability. Treated textile dye wastewater is considered a potential controlled process-resource after appropriate treatment and contaminant assessment. The overall pathway changes the conventional **waste → disposal approach into waste → recovery → material production → useful product → appropriate end-of-life management**. This integrated approach has the potential to reduce agricultural waste, support resource recovery, and reduce dependence on conventional plastics. However, the proposed pathway remains conceptual and requires experimental, safety, environmental, and life-cycle validation.

7. Results and Discussion

Because the present study is based on secondary research, the results presented in this section represent a synthesis of findings reported in the reviewed literature rather than experimentally measured results for BioFlex EcoPlast™. The evidence indicates that individual components have complementary functions, while their integrated use provides a promising conceptual pathway for developing a biodegradable multi-waste composite.

7.1 Banana Peel Bioplastic Properties

The reviewed literature indicates that banana peel has potential as a biodegradable matrix/feedstock because it contains starch, cellulose, hemicellulose, lignin, pectin, and other organic constituents. In the attached study, banana-peel flour was combined with cellulose and plasticizers to produce bioplastic formulations. The optimized formulation reported a tensile strength of approximately 2.40 MPa, demonstrating the feasibility of banana peel as a bioplastic material but also indicating limitations in mechanical strength when compared with stronger conventional plastic materials. The study also showed that formulation differences affected tensile behavior, breaking characteristics, thickness, and water-vapor permeability. Therefore, banana peel is considered suitable as the biodegradable matrix of BioFlex EcoPlast™, but reinforcement and formulation optimization are necessary for improved performance.

7.2 Bagasse Reinforcement Effects

Sugarcane bagasse is identified as a cellulose-, hemicellulose-, and lignin-containing agricultural residue with potential for composite reinforcement. The reviewed literature indicates that pretreatment can improve cellulose accessibility and fibre–matrix interaction. Consequently, bagasse can potentially contribute to stiffness, structural stability, and waste valorization in BioFlex EcoPlast™. However, excessive loading or poor dispersion may adversely affect composite uniformity and flexibility.

7.3 Banana Fibre Reinforcement

Banana fibre provides a complementary reinforcement pathway because it is a cellulose-rich agricultural residue. Its proposed function is to improve tensile strength and load transfer within the banana-peel matrix. The combination is theoretically advantageous because banana peel supplies the biodegradable matrix while banana fibre provides structural reinforcement. Nevertheless, fibre treatment, length, loading, dispersion, and matrix compatibility can significantly influence the final composite properties.

7.4 Wastewater Reuse Feasibility

The literature provides stronger evidence for textile wastewater treatment and industrial reuse than for direct incorporation of treated textile wastewater into biodegradable plastics. Treatment technologies include coagulation–flocculation, adsorption, membrane separation, biological processes, electrochemical treatment, and advanced oxidation. Therefore, its use in BioFlex EcoPlast™ remains an emerging conceptual possibility requiring contaminant removal, chemical characterization, toxicity assessment, and safety validation before practical application.

7.5 Integrated BioFlex EcoPlast™ Model

The synthesized evidence supports a conceptual multi-component composite structure in which banana peel acts as the biodegradable matrix, sugarcane bagasse and banana fibre provide reinforcement, and plasticizer contributes flexibility and processability. Treated textile wastewater is positioned separately as a controlled process-resource rather than a conventional structural ingredient. This functional allocation is consistent with the proposed conceptual framework.

7.6 Comparative Analysis

The literature suggests that combining complementary waste-derived components may address limitations observed in single-source bioplastics. Banana-peel materials alone may have limited mechanical strength, whereas natural fibres and bagasse can potentially improve structural performance. However, it would be scientifically inappropriate to state that multi-waste systems experimentally outperform single-source bioplastics because BioFlex EcoPlast™ has not yet been fabricated or tested. The present evidence supports only the potential for complementary performance through optimized matrix–fibre integration.

7.7 Sustainability Assessment

From a sustainability perspective, BioFlex EcoPlast™ offers a conceptual pathway for converting banana peel, sugarcane bagasse, banana fibre, and appropriately treated textile wastewater into potential material resources. This approach supports agricultural-waste valorization, resource recovery, reduced dependence on virgin plastic resources, and circular-economy principles. The proposed pathway connects waste generation with material recovery and product development. However, the environmental superiority of the system cannot yet

be confirmed without life-cycle assessment, techno-economic analysis, toxicity assessment, and experimental validation.

8. Limitations

The present study has several limitations that should be considered when interpreting the proposed BioFlex EcoPlast™ system. First, the study is based on secondary research and conceptual synthesis, and therefore the proposed composite has not been experimentally fabricated or tested. Consequently, the expected mechanical strength, flexibility, water resistance, thermal stability, and biodegradability remain to be experimentally validated. Second, considerable variability exists among published studies because researchers use different raw-material compositions, fibre treatments, plasticizer concentrations, processing conditions, and testing standards. This makes direct comparison of reported material properties difficult. Third, although substantial research exists on textile wastewater treatment and industrial water reuse, relatively few studies have investigated the direct use of appropriately treated textile dye wastewater as a process resource in biodegradable composite-plastic production. Therefore, its role in BioFlex EcoPlast™ remains conceptual and requires chemical, toxicity, and safety assessment. Finally, scale-up uncertainty remains because laboratory-scale formulations may behave differently during continuous processing or industrial production. Factors such as raw-material availability, mixing uniformity, processing energy, cost, quality control, and wastewater-treatment requirements must be evaluated before commercial implementation. Future experimental and pilot-scale studies are therefore necessary to establish the technical and environmental feasibility of BioFlex EcoPlasT.

9. Future Research

Future research should focus on the experimental validation and practical development of BioFlex EcoPlast™. Laboratory-scale experiments should first be conducted to determine the optimum proportions of banana peel, sugarcane bagasse, banana fibre, plasticizer, and treated textile dye wastewater. The resulting composites should be evaluated for tensile strength, elongation, water absorption, thermal stability, morphology, and biodegradation under standardized testing conditions.

A comprehensive life-cycle assessment (LCA) should then be performed to compare BioFlex EcoPlast™ with conventional plastics and other biodegradable materials in terms of energy consumption, greenhouse-gas emissions, water use, waste reduction, and end-of-life impacts. Industrial scaling should investigate continuous processing, raw-material availability,

production cost, quality consistency, energy requirements, and wastewater-treatment integration.

Particular attention should be given to toxicity and environmental-safety studies, especially because treated textile dye wastewater is proposed as a process-resource. Residual dyes, heavy metals, organic contaminants, and potential leaching from the final composite should be assessed before practical application.

Finally, future studies may investigate nanofibre or nanocellulose reinforcement derived from banana fibre or sugarcane bagasse. Such reinforcement could potentially improve tensile strength, barrier properties, and structural stability at relatively low loading levels. These investigations would help determine whether BioFlex EcoPlast™ can progress from a conceptual multi-waste material to a technically validated and scalable sustainable plastic alternative.

Conclusion

The present secondary study concludes that BioFlex EcoPlast™ represents a promising conceptual approach for integrating agricultural and industrial waste streams into a biodegradable composite material. The literature indicates that banana peel has potential as a biodegradable matrix/feedstock but requires reinforcement to overcome limitations in mechanical strength and moisture resistance. Sugarcane bagasse can potentially contribute stiffness and structural stability, while banana fibre may enhance tensile strength and load transfer within the composite. Plasticizer optimization is also important to achieve an appropriate balance between strength, flexibility, and processability.

The study further identifies treated textile dye wastewater as a potential controlled process-resource within the proposed circular-economy model. However, its application remains conceptual and requires adequate treatment, contaminant removal, chemical characterization, toxicity assessment, and safety validation.

Overall, the findings suggest that integrating multiple waste materials could provide a more comprehensive waste-valorization pathway than single-source bioplastic systems. The proposed framework connects agricultural waste recovery, industrial wastewater resource recovery, biodegradable material development, and sustainable end-of-life management. However, BioFlex EcoPlast™ has not yet been experimentally fabricated or validated; therefore, its high-strength performance and environmental superiority cannot currently be claimed as established results. Future experimental studies should optimize formulation and evaluate mechanical, thermal, water-resistance, biodegradation, toxicity, life-cycle, and techno-economic performance. Thus, this research provides a literature-based conceptual

foundation for future development of a scientifically validated, scalable, and sustainable multi-waste biodegradable composite plastic.

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