CIRCULAR URBAN GOVERNANCE FRAMEWORK USING HYBRID BIOFILLER REINFORCED POLYVINYL ESTER COMPOSITE TECHNOLOGY FOR MUNICIPAL WASTE REUTILIZATION

S.Vinodh*[1], C.Dhavamani[1]

*[1]Assistant Professor, Department of Aeronautical Engineering, Mahendra Engineering College, Mallasamudharam, Namakkal. 637503. India
[1]Professor, Mahendra Engineering College, Mallasamudharam, Namakkal. 637503. India
*Corresponding author: vinodhsekar.aero@gmail.com
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Abstract: Rapid urbanization and increasing municipal waste accumulation have intensified environmental challenges associated with non-biodegradable and food-derived waste materials. The present study introduces a circular urban waste governance framework for the development of hybrid biofiller composites using recycled urban waste resources. Discarded cigarette filter fibers and processed eggshell powder were utilized as reinforcement and filler materials within a polyvinyl ester matrix system to produce eco-oriented composite structures. The developed composites were fabricated using a compression molding approach and evaluated through tensile, flexural, impact, hardness, thermal, and morphological analyses based on standardized testing procedures. Experimental results demonstrated notable improvements in structural integrity, surface hardness, thermal resistance, and impact behavior with the incorporation of hybrid biofillers. Enhanced interfacial bonding and effective stress transfer mechanisms contributed significantly toward improved composite performance. Thermal investigations further confirmed that the addition of calcium carbonate-rich eggshell particles improved degradation resistance and thermal stability. In addition to material characterization, the study proposes a decentralized municipal waste reutilization model integrating waste segregation, resource recovery, and circular economy implementation within local self-government systems. The proposed framework supports sustainable urban administration by reducing landfill burden, minimizing environmental contamination, and transforming problematic urban wastes into value-added engineering materials. The investigation establishes that hybrid biofiller composite technology can serve as an effective interdisciplinary solution connecting urban waste governance, resource-efficient manufacturing, and circular economy-oriented sustainable development.

Keywords: Circular urban governance, Hybrid biofiller composite, Municipal waste reutilization, Resource recovery, Circular economy

1. INTRODUCTION

Rapid urbanization and population growth have significantly increased the generation of municipal solid waste across developing and developed nations. Among the various categories of urban waste, cigarette filter waste and food-derived waste materials have emerged as major environmental concerns due to their large disposal volume and poor biodegradability. Discarded cigarette filters are one of the most frequently observed litter materials in urban streets, drainage systems, transportation hubs, and public spaces. The continuous increase in tobacco consumption has intensified the accumulation of cigarette butt waste in cities, thereby creating serious ecological and public health challenges [1]. Studies indicate that several trillion cigarette filters are discarded annually worldwide, leading to enormous quantities of persistent waste entering terrestrial and aquatic ecosystems [2]. The situation is expected to worsen further with the increasing number of smokers and urban population expansion [3].

Cigarette filters are primarily composed of cellulose acetate fibers, which exhibit extremely slow degradation behavior under natural environmental conditions [4]. Due to their non-biodegradable characteristics, these wastes remain in the environment for prolonged periods and contribute to visual pollution, soil contamination, drainage blockage, and water toxicity [5]. In many urban regions, discarded cigarette filters are commonly deposited in roadsides, public spaces, and water runoff channels, where toxic chemicals leach into nearby ecosystems [6]. Several environmental investigations have reported that the chemical constituents present in cigarette waste can negatively affect aquatic organisms and microbial activity within soil systems [7]. Consequently, municipal authorities and local self-government bodies are facing increasing pressure to establish sustainable strategies for the collection, segregation, and reutilization of such difficult-to-manage urban wastes.

Simultaneously, food-processing waste generated from domestic kitchens, restaurants, hotels, and food industries also represents a major environmental management challenge for local administrations. Eggshell waste is one of the most abundantly generated bio-waste materials across urban and semi-urban communities due to the extensive consumption of poultry eggs [8]. A substantial quantity of eggshell waste is disposed of directly into landfill sites without undergoing any beneficial recovery process. Such uncontrolled disposal practices create sanitation concerns, unpleasant odor generation, and microbial contamination risks in municipal dumping locations [9]. Since eggshells contain high quantities of calcium carbonate and other mineral constituents, improper disposal leads to the underutilization of potentially valuable natural resources [10]. Therefore, identifying sustainable utilization pathways for eggshell waste has become an important aspect of circular economy implementation and sustainable urban waste governance.

Recent developments in environmental sustainability research have emphasized the importance of converting waste materials into value-added engineering resources rather than treating them solely as disposal burdens [11]. In this context, polymer composite technology has emerged as an effective platform for incorporating waste-derived materials into sustainable engineering applications. Fiber-reinforced polymer composites are widely utilized in automotive, aerospace, marine, structural, and consumer product sectors because of their lightweight nature, corrosion resistance, and favorable mechanical performance [12]. The incorporation of waste fibers and bio-fillers into polymer matrices can significantly improve resource efficiency while simultaneously reducing environmental pollution associated with urban waste accumulation [13].

Polyvinyl ester resin has attracted considerable attention in composite fabrication owing to its favorable mechanical strength, low shrinkage characteristics, chemical resistance, and superior interfacial adhesion capability [14]. Compared with conventional thermosetting matrices, polyvinyl ester exhibits enhanced wettability and processing characteristics, making it suitable for sustainable composite development involving recycled reinforcement materials [15]. Furthermore, the inclusion of bio-based fillers within polymer matrices has demonstrated the potential to improve stiffness, dimensional stability, and interfacial bonding characteristics of composite systems [16]. Researchers have reported that eggshell powder acts as an effective natural filler due to its high calcium carbonate content, low density, affordability, and environmental compatibility [17]. The integration of eggshell-derived fillers into polymer systems has shown positive effects on tensile, flexural, hardness, and impact performance [18].

In recent years, several investigations have explored the utilization of natural fibers, agricultural residues, and industrial waste materials for sustainable composite production. Previous studies have demonstrated that waste-derived fillers and fibers can improve the structural and functional properties of polymer composites while reducing manufacturing costs and ecological impacts [19]. Similarly, cigarette filter fibers have also been investigated as potential reinforcement materials because of their fibrous morphology and availability in large quantities [20]. However, most existing studies have primarily concentrated on material characterization and mechanical optimization perspectives, with limited attention given to the broader environmental governance and municipal waste management implications associated with such recycling approaches.

Local self-government institutions play a vital role in implementing sustainable urban waste management policies and promoting circular economy practices at the community level. Municipal administrations are increasingly expected to develop decentralized waste recovery systems capable of transforming problematic waste streams into economically beneficial products [21]. Integrating engineering-based waste reutilization technologies with local governance frameworks can contribute significantly toward landfill reduction, environmental conservation, and sustainable urban development. Waste-to-resource initiatives supported by municipalities may also generate employment opportunities, strengthen recycling infrastructure, and encourage public participation in environmental sustainability programs [22].

Despite growing awareness regarding sustainable material development, there remains a substantial research gap concerning the integration of cigarette filter waste and eggshell waste within local governance-oriented recycling frameworks. Existing literature lacks comprehensive investigations addressing how municipal waste streams can be systematically converted into sustainable composite materials through environmentally responsible management strategies. Furthermore, limited studies have examined the role of local administrations in facilitating the collection, segregation, processing, and reuse of urban cigarette and food wastes within a circular economy model.

Therefore, the present study proposes a sustainable local self-government strategy for recycling urban cigarette filter waste and eggshell waste into eco-friendly composite materials. The investigation focuses on developing polyvinyl ester-based composites reinforced with recycled cigarette filter fibers and eggshell powder fillers while evaluating their mechanical and thermal characteristics. In addition to material performance assessment, the study highlights the environmental significance of decentralized waste reutilization and emphasizes the importance of municipal-level circular economy implementation. The proposed approach aims to support sustainable urban governance by providing an integrated framework for waste reduction, resource recovery, and environmentally responsible composite material development.

2. LITERATURE SURVEY

The rapid increase in urban solid waste generation has created substantial environmental and administrative challenges for municipal authorities and local self-government institutions worldwide. Among various urban waste streams, cigarette filter waste and food-derived bio-waste have emerged as major contributors to environmental pollution due to their high disposal rates and limited biodegradability. Recent sustainability-oriented investigations have focused on converting these waste materials into value-added engineering products to support circular economy objectives and environmentally responsible waste management systems. Polymer composite technology has become an important research area in this context because it enables the incorporation of recycled fibers and bio-fillers into functional structural materials with reduced environmental impact [1].

Discarded cigarette filters represent one of the most dominant forms of urban litter generated globally. Researchers have reported that cigarette filters contain cellulose acetate fibers, which exhibit poor biodegradability and remain in the environment for prolonged durations [2]. Continuous disposal of cigarette waste in public spaces, drainage channels, and water bodies contributes to ecological contamination and visual pollution [3]. Environmental investigations have demonstrated that cigarette butt leachates can negatively influence aquatic organisms and soil microbial activities, thereby increasing concerns regarding urban environmental sustainability [4]. Due to these challenges, researchers have explored several recycling and reuse approaches for cigarette filter waste to minimize landfill accumulation and promote sustainable resource recovery systems.

Polymer composites reinforced with waste-derived fibers have gained significant attention because of their lightweight characteristics, corrosion resistance, and favorable mechanical performance [5]. Fiber-reinforced polymer composites are extensively utilized in aerospace, marine, construction, transportation, and consumer applications owing to their high specific strength and durability [6]. Among different thermosetting matrices, polyvinyl ester resin has emerged as a promising material for sustainable composite fabrication due to its superior wettability, improved adhesion characteristics, low shrinkage behavior, and enhanced chemical resistance [7]. The compatibility of polyvinyl ester resin with recycled reinforcement materials has encouraged researchers to investigate its application in environmentally sustainable composite systems.
Several investigations have concentrated on utilizing agricultural residues and natural bio-fillers to improve the mechanical and thermal characteristics of polymer composites. Eggshell powder has become one of the most promising waste-derived fillers because of its high calcium carbonate composition, low density, biodegradability, and wide availability [8]. Large quantities of eggshell waste generated from households, restaurants, food industries, and commercial establishments are commonly disposed of into landfills without any effective recovery mechanism [9]. Improper disposal of eggshell waste contributes to sanitation issues and environmental degradation, thereby emphasizing the necessity for sustainable reutilization methods.

Researchers have reported that the incorporation of eggshell powder into polymer matrices can significantly improve stiffness, hardness, interfacial bonding, and dimensional stability of composite materials [10]. The calcium carbonate-rich structure of eggshell particles enhances stress transfer capability between reinforcement and matrix phases, thereby improving tensile and flexural performance [11]. Furthermore, eggshell fillers have demonstrated positive effects on thermal stability due to their ability to reduce polymer degradation rates under elevated temperature conditions [12]. These characteristics make eggshell powder a suitable sustainable filler material for eco-friendly composite development.

Ganesan et al. investigated the mechanical behavior of polyester composites reinforced with jute fibers and eggshell powder fillers [13]. Their study reported that alkali-treated natural fiber composites containing optimized eggshell filler content exhibited improved tensile and flexural performance compared with conventional composites. Similarly, Oladele et al. fabricated sisal fiber-reinforced epoxy composites containing eggshell filler and observed enhancement in interfacial adhesion and mechanical strength [14]. Their investigation concluded that lower filler concentrations contributed to improved load transfer efficiency and reduced crack propagation within the composite structure. Balaji et al. explored the utilization of discarded cigarette filters and coconut coir fibers in polyester-based composite fabrication [15]. The study demonstrated that cigarette filter fibers could effectively function as reinforcement materials in lightweight structural composites. The inclusion of filler materials improved impact resistance up to an optimal concentration, beyond which agglomeration effects reduced composite performance. Similarly, Owuamanam et al. examined the influence of eggshell particles in limestone-reinforced epoxy composites and reported that lower filler loading percentages produced improved mechanical properties and better matrix compatibility [16].

Ashok Kumar et al. investigated eggshell powder-filled jute-epoxy composites and reported considerable enhancement in tensile strength, flexural strength, and hardness properties with increasing eggshell filler content [17]. Their findings highlighted the capability of eggshell particles to improve composite rigidity and resistance against deformation. The study further demonstrated that eggshell fillers contributed to improved structural integrity by reducing stress concentration regions within the matrix.

Table 1 Comparison of Existing Studies

Authors	Reinforcement / Filler Material	Matrix Material	Major Findings	Research Limitation
Ganesan et al. [13]	Jute fiber with eggshell powder and nanoclay	Polyester	Improved tensile and flexural properties with optimized filler addition	Focused only on mechanical performance
Balaji et al. [15]	Cigarette filters and coconut coir	Polyester	Enhanced impact behavior up to optimal filler concentration	No environmental governance discussion
Owuamanam et al. [16]	Eggshell particles with limestone	Epoxy	Better properties at lower filler loading	Did not address municipal waste utilization
Shobhit Dixit et al. [18]	Hemp fiber bio-composite	Polypropylene/ Polyethylene	Enhanced eco-friendly packaging performance	Focused on optimization methodology
Saravanakumar et al. [19]	Banana fiber composites	Epoxy	High prediction accuracy using ANN and RSM	No urban waste management framework

Recent sustainability-oriented investigations have also explored statistical and predictive modeling approaches for evaluating composite behavior. Shobhit Dixit et al. utilized response surface methodology to optimize the properties of hemp fiber-based bio-composites intended for environmentally sustainable packaging applications [18]. Their study confirmed that natural fiber treatment and filler incorporation significantly affected composite performance characteristics. Saravanakumar et al. integrated artificial neural network models with experimental investigations to evaluate banana fiber-reinforced epoxy composites [19]. Their findings demonstrated that optimized reinforcement conditions could produce enhanced tensile, flexural, and impact properties.

The integration of waste recycling technologies into local governance systems can significantly contribute toward landfill reduction, environmental sustainability, and urban resource efficiency [21]. Sustainable composite development using urban cigarette and eggshell waste provides an opportunity for municipalities to transform problematic waste streams into economically beneficial engineering products. Such approaches support decentralized recycling practices and encourage community participation in environmental conservation initiatives. Furthermore, waste valorization strategies can reduce pressure on landfill infrastructure and support sustainable development objectives through responsible material recovery systems [22].

Although numerous studies have investigated waste-derived composites from mechanical and material engineering perspectives, limited research has addressed the environmental governance and municipal waste management implications associated with these sustainable recycling strategies. Existing investigations primarily focus on optimization techniques, mechanical characterization, and structural performance analysis while neglecting the role of local self-government systems in implementing decentralized waste reutilization frameworks [20]. Urban local bodies play a critical role in promoting waste segregation, recycling infrastructure development, public awareness programs, and circular economy implementation at the municipal level.

Despite growing environmental concerns and increasing interest in circular economy implementation, a significant research gap remains regarding the integration of cigarette filter waste and eggshell waste within local self-government-oriented sustainability frameworks. Limited investigations have examined how municipal waste management systems can support the conversion of urban waste streams into eco-friendly composite materials while simultaneously promoting environmental governance and sustainable resource utilization. Therefore, the present study attempts to bridge this gap by developing sustainable composite materials using recycled cigarette filter fibers and eggshell powder while emphasizing the role of local self-government strategies in supporting circular urban waste management systems.

3. PROPOSED METHODOLOGY

3.1 Introduction

The present investigation proposes an integrated circular urban waste governance framework for the development of hybrid biofiller polymer composites using recycled urban waste resources. The methodology combines sustainable waste recovery, green composite manufacturing, material performance evaluation, and decentralized municipal waste reutilization strategies within a unified circular economy framework. Unlike conventional engineering-oriented methodologies focused primarily on optimization and statistical prediction, the proposed approach emphasizes environmentally responsible resource recovery and urban sustainability implementation through hybrid biofiller composite technology.

The methodology was designed to transform problematic municipal waste streams into value-added engineering resources through organized waste collection, preprocessing, eco-friendly fabrication, and structural evaluation procedures. The developed framework supports local self-government initiatives by demonstrating how urban cigarette waste and food-derived bio-waste can be integrated into circular economy systems capable of reducing landfill accumulation and environmental pollution.

The overall research methodology adopted in the present study is illustrated in Figure 3.1.

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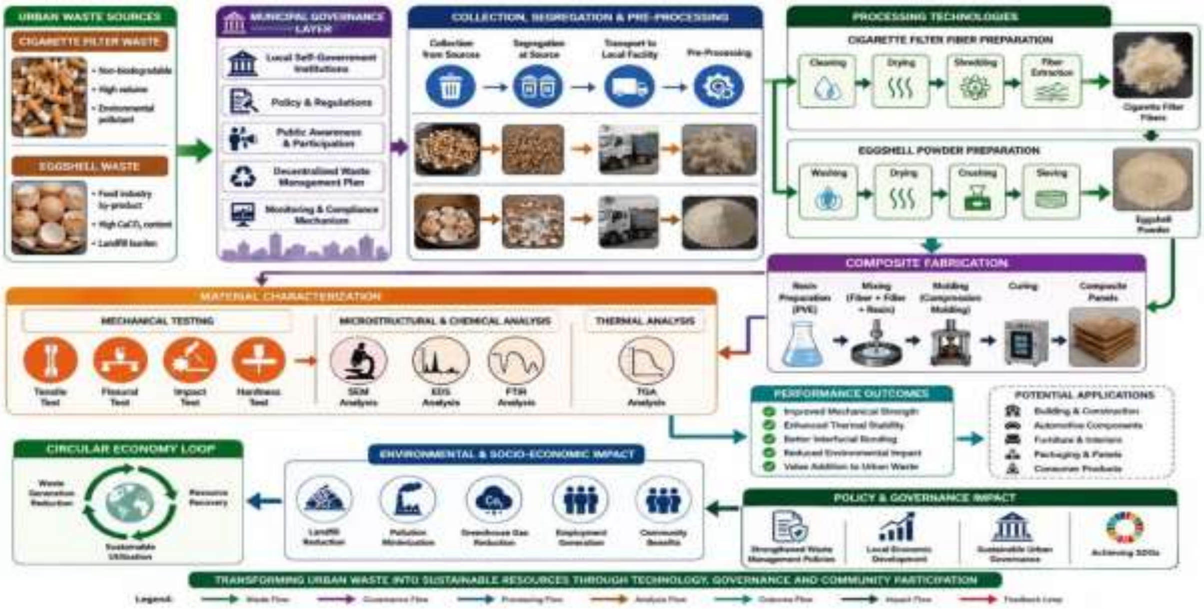
Fig 3.1 Overall sustainable waste reutilization framework



3.2 Circular Urban Waste Collection Framework

The first stage of the methodology involves the systematic collection and segregation of urban waste materials from decentralized municipal sources. Used cigarette filter fibers and eggshell waste were selected as the primary hybrid biofiller resources because of their widespread availability, environmental persistence, and increasing accumulation in urban environments.

Fig 3.2 Urban Waste Resource Collection and Segregation System

Discarded cigarette filters were collected from tea shops, restaurants, transportation hubs, public smoking areas, and roadside waste accumulation zones. Cigarette filter waste represents one of the largest non-biodegradable urban litter materials because of its cellulose acetate composition and prolonged environmental degradation period. Improper disposal of these materials causes drainage blockage, soil contamination, and water pollution within urban ecosystems.

Similarly, eggshell waste was collected from food establishments, hotels, restaurants, and domestic kitchens. Eggshells constitute a significant portion of food-derived municipal waste and are commonly disposed of into landfills without beneficial reutilization. Since eggshells contain calcium carbonate-rich constituents, their recovery and utilization support sustainable resource efficiency and circular urban waste management practices.

The proposed waste collection framework promotes decentralized municipal participation and community-level waste segregation mechanisms to support sustainable urban governance.

3.3 Hybrid Biofiller Resource Recovery Model

After collection, the waste materials underwent preprocessing operations to improve cleanliness, compatibility, and suitability for composite fabrication. The preprocessing stage was designed to minimize additional chemical usage while maintaining environmental sustainability principles.

The collected cigarette filters were manually cleaned to remove residual tobacco particles, paper wrapping, and external contaminants. The fibers were immersed in distilled water and subjected to multiple washing cycles to eliminate odor, nicotine residues, and hazardous contaminants. After cleaning, the fibers were dried under sunlight conditions to remove absorbed moisture and improve fiber-matrix adhesion characteristics during fabrication.

Unlike conventional surface modification methods involving alkali or silane treatment, the present investigation utilized untreated cigarette fibers to support environmentally sustainable and low-cost recycling implementation.

The eggshell waste materials were washed thoroughly to remove organic membrane residues and contaminants. After drying, the eggshells were mechanically crushed and converted into fine powder form using grinding equipment. The prepared eggshell powder was sieved to ensure uniform particle distribution before incorporation into the matrix system.

The hybrid biofiller preparation procedure is illustrated in Figure 3.3.

Fig 3.3 Hybrid Biofiller Recovery and Preparation Process

3.4 Green Matrix Selection Strategy

Polyvinyl ester resin was selected as the matrix material for the development of the proposed hybrid biofiller composite because of its favorable structural, thermal, and adhesion characteristics. Polyvinyl ester exhibits superior wettability, lower shrinkage behavior, and enhanced compatibility with reinforcement materials compared with conventional thermosetting polymer systems.

The matrix system consisted of polyvinyl ester resin along with methyl ethyl ketone peroxide catalyst and cobalt octoate accelerator to facilitate polymerization and curing. The selected matrix system supports room-temperature curing and simplifies manufacturing operations suitable for decentralized composite production systems.

The utilization of polyvinyl ester resin contributes toward lightweight structural performance and improved stress transfer capability between reinforcement fibers and filler particles.

3.5 Green Composite Manufacturing Architecture

The developed hybrid biofiller composites were fabricated using a compression molding process assisted by manual lay-up techniques. Compression molding was selected because of its simplicity, lower processing cost, reduced energy requirement, and compatibility with recycled reinforcement systems.
Different weight percentages of eggshell powder filler were incorporated into the polyvinyl ester matrix while maintaining cigarette filter fiber reinforcement within the composite structure. Continuous stirring was performed to ensure uniform filler dispersion and improved interfacial interaction.

After achieving homogeneous mixing, catalyst and accelerator were introduced into the matrix system. The processed cigarette filter fibers were then distributed within the mold cavity, followed by the addition of the prepared resin-filler mixture. The fabricated composite was subjected to compression molding under controlled pressure and temperature conditions.
The manufactured composites were cured at room temperature for twenty-four hours to ensure complete polymerization and structural stabilization. The green composite manufacturing process is illustrated in Figure 3.4.

Fig 3.4 Green Composite Manufacturing Architecture

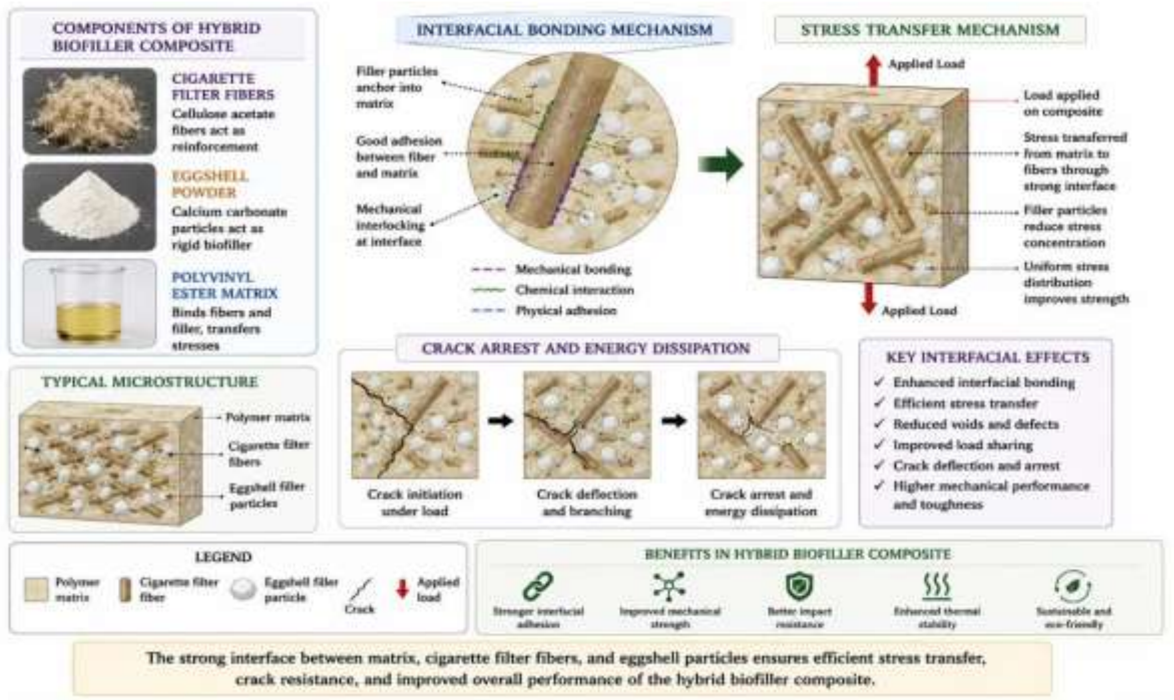
3.6 Interfacial Reinforcement Mechanism

The developed hybrid biofiller system improves composite performance through enhanced interfacial bonding between matrix, reinforcement fibers, and filler particles. The incorporation of eggshell powder promotes better adhesion characteristics because of its calcium carbonate-rich composition.

During loading conditions, externally applied stresses are transferred effectively from the matrix phase toward reinforcement fibers through the filler-supported interfacial network. The filler particles reduce stress concentration zones and improve matrix compactness, thereby minimizing crack propagation and premature structural failure.

The randomly distributed cigarette filter fibers contribute toward multidirectional stress transfer capability, while the rigid eggshell particles improve stiffness and resistance against localized deformation. The proposed interfacial reinforcement mechanism is illustrated in Figure 3.5.

Fig 3.5 Interfacial Reinforcement and Stress Transfer Mechanism



3.7 Sustainable Performance Evaluation Framework

The fabricated composites were subjected to structural and thermal performance evaluation according to ASTM standards. The evaluation framework focused on determining the suitability of the developed hybrid biofiller composites for lightweight engineering and urban sustainability applications.

The following analyses were conducted:

- Tensile strength analysis
- Flexural strength analysis
- Impact resistance analysis
- Hardness evaluation
- Thermal stability analysis
- Morphological investigation

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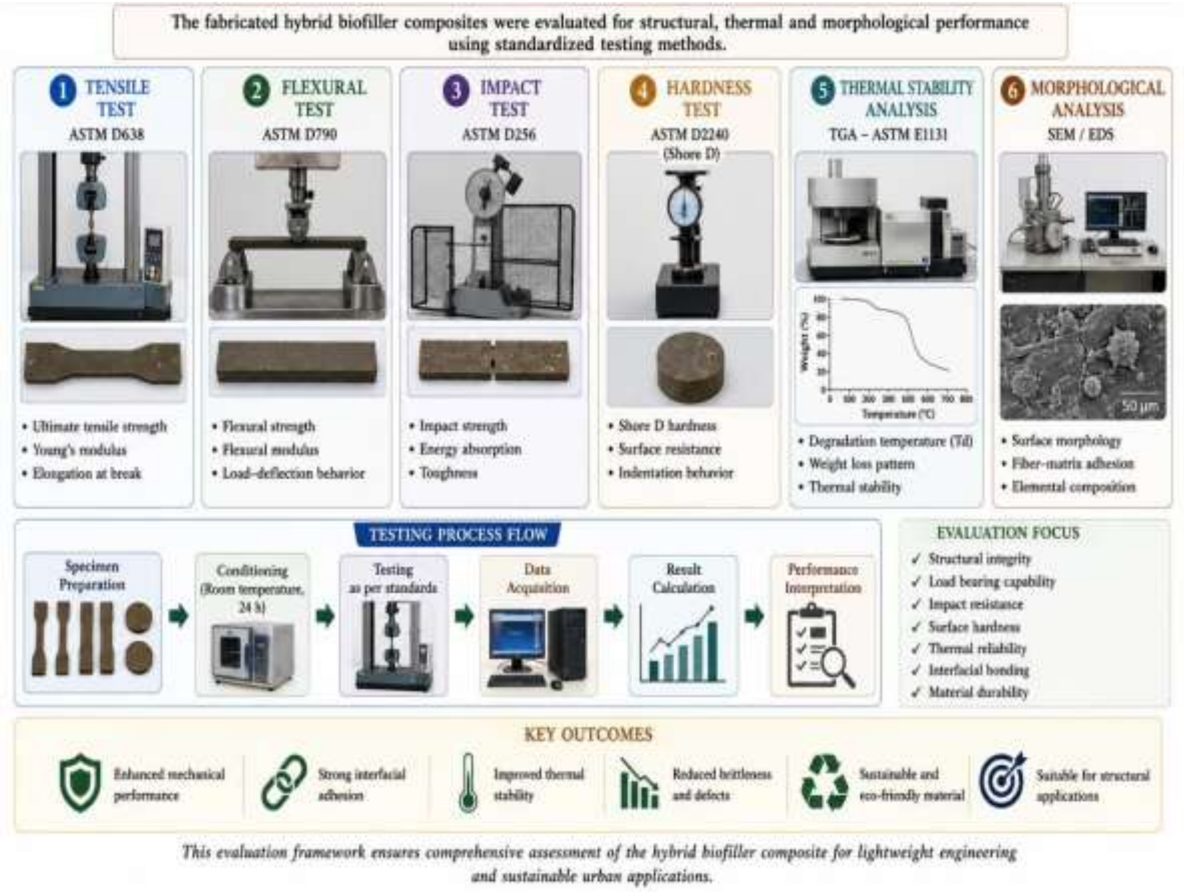
The structural characterization framework is illustrated in Figure 3.6.

Fig 3.6 Sustainable Composite Performance Evaluation Framework



3.8 Municipal Circular Economy Integration Model

The proposed methodology extends beyond conventional composite fabrication by integrating municipal circular economy implementation strategies within the hybrid biofiller development framework.

The developed model supports:

- decentralized waste segregation
- community-level recycling
- urban resource recovery
- landfill reduction
- municipal sustainability programs
- circular economy implementation

Local self-government institutions can collaborate with restaurants, commercial establishments, recycling agencies, and public waste management systems to establish organized collection and processing channels for hybrid biofiller resource recovery. The proposed circular economy integration model is illustrated in Figure 3.7.

Fig 3.7 Municipal Circular Economy Integration Model

3.9 Environmental Impact Reduction Strategy

The proposed methodology contributes significantly toward sustainable urban development and environmental pollution reduction by transforming problematic municipal waste streams into value-added engineering resources.

The reutilization of discarded cigarette filters minimizes non-biodegradable urban litter accumulation, while eggshell waste recovery supports organic waste reduction and resource efficiency. The proposed hybrid biofiller framework also reduces landfill dependency and promotes decentralized recycling implementation.

Furthermore, the methodology aligns with circular economy principles through waste-to-resource conversion and sustainable material development. The proposed framework therefore establishes an interdisciplinary model integrating environmental engineering, municipal governance, and circular urban sustainability systems.

4. RESULTS AND DISCUSSION

4.1 Overview of Experimental Findings

The experimental investigation demonstrated that the incorporation of recycled cigarette filter fibers and eggshell powder significantly influenced the structural, thermal, and mechanical performance of the developed polyvinyl ester composite system. The results indicate that sustainable urban waste materials can be effectively converted into value-added engineering composites while simultaneously supporting circular economy objectives and environmentally responsible municipal waste management practices.

The fabricated composites exhibited noticeable improvement in tensile strength, flexural behavior, impact resistance, hardness characteristics, and thermal stability with the addition of eggshell powder filler. The enhancement in composite performance can be attributed to improved interfacial bonding, effective stress transfer mechanisms, and better filler dispersion within the polymer matrix.

Unlike conventional optimization-oriented composite investigations, the present study emphasizes sustainable material utilization and environmental significance rather than statistical parameter optimization. Therefore, the obtained results are discussed from the perspective of waste valorization, composite performance enhancement, and potential municipal sustainability applications.

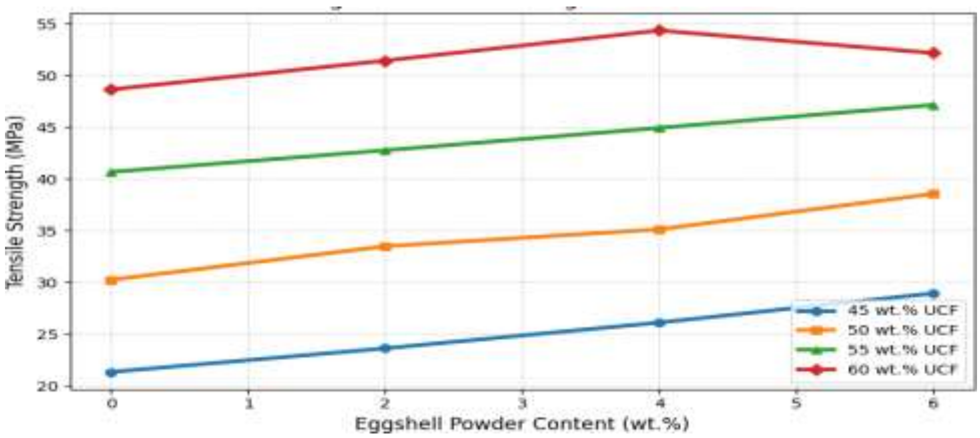
4.2 Mechanical Performance of Cigarette Filter Fiber Composites

4.2.1 Tensile Strength Analysis

The tensile strength behavior of the fabricated composites demonstrated progressive improvement with increasing eggshell powder addition. The developed composites reinforced with recycled cigarette filter fibers exhibited enhanced load-carrying capability compared with filler-free composite systems.

The tensile behavior of the fabricated composites is illustrated in Figure 4.1.

Fig.4.1 Tensile Strength Table 4.1 Output responses



Run Order	UCF (wt.%)	ESP (wt.%)	UCF Length (mm)	TS (MPa)	FS (MPa)	IS (J/m)	HS (Barcol)	Standard Order
1	45	0	5	21.34	14.55	2.45	15.22	2
2	45	2	10	23.62	16.84	2.88	17.11	6
3	45	4	15	26.11	18.92	3.94	20.43	9
4	45	6	20	28.94	21.47	4.76	23.68	8
5	50	0	10	30.25	23.68	5.12	25.44	1
6	50	2	5	33.48	25.89	5.84	27.96	12
7	50	4	20	35.12	27.55	6.15	30.12	4
8	50	6	15	38.55	30.44	6.88	33.25	7
9	55	0	15	40.66	31.88	7.22	35.74	13
10	55	2	20	42.75	33.96	7.65	38.16	15
11	55	4	5	44.92	35.75	8.02	41.58	11
12	55	6	10	47.14	37.89	8.36	44.27	10
13	60	0	20	48.63	39.15	8.75	46.83	3

14	60	2	15	51.42	40.74	9.12	49.44	14
15	60	4	10	54.33	42.88	9.46	52.11	16
16	60	6	5	52.15	41.25	9.84	54.36	5

The observed enhancement in tensile strength can be attributed to improved interfacial adhesion between the polymer matrix, reinforcement fibers, and eggshell filler particles. Eggshell powder contains calcium carbonate-rich constituents that promote better stress distribution and improve the compatibility between matrix and reinforcement phases.

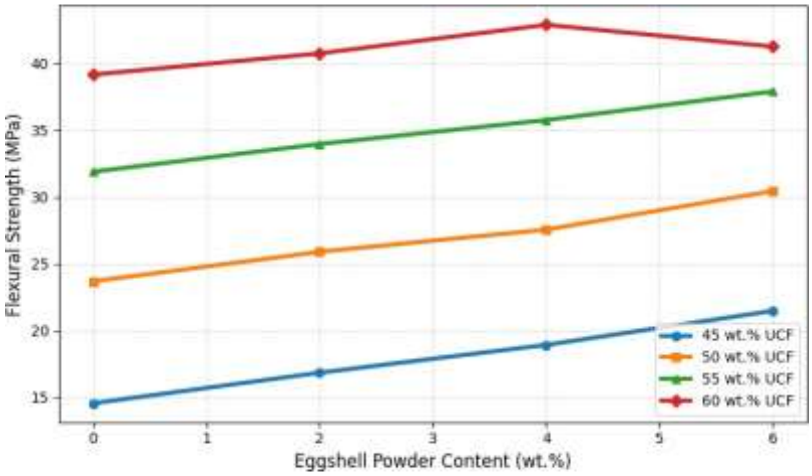
As the filler concentration increased, the polymer matrix exhibited greater resistance against tensile deformation due to effective load transfer from the matrix to the reinforcement fibers. The inclusion of rigid filler particles also reduced the possibility of stress concentration zones and delayed crack initiation during tensile loading. However, excessive filler concentration may potentially produce particle agglomeration and weak interfacial regions, which can reduce mechanical efficiency. Nevertheless, the present study demonstrated that controlled eggshell filler addition significantly improved the tensile properties of sustainable waste-derived composites.

The tensile strength results obtained for different composite compositions are summarized in Table 4.1.

4.3 Flexural Strength Behavior

Flexural testing was conducted to evaluate the bending resistance and structural rigidity of the fabricated composites. The results indicated that the incorporation of eggshell powder improved the flexural strength characteristics of the developed composite system.

Fig.4.2 Flexural strength



The enhancement in flexural behavior is primarily associated with improved interlocking mechanisms between the matrix and reinforcement phases. During bending conditions, the stress generated within the matrix was effectively transferred toward the cigarette filter fibers and filler particles, thereby improving resistance against crack propagation.

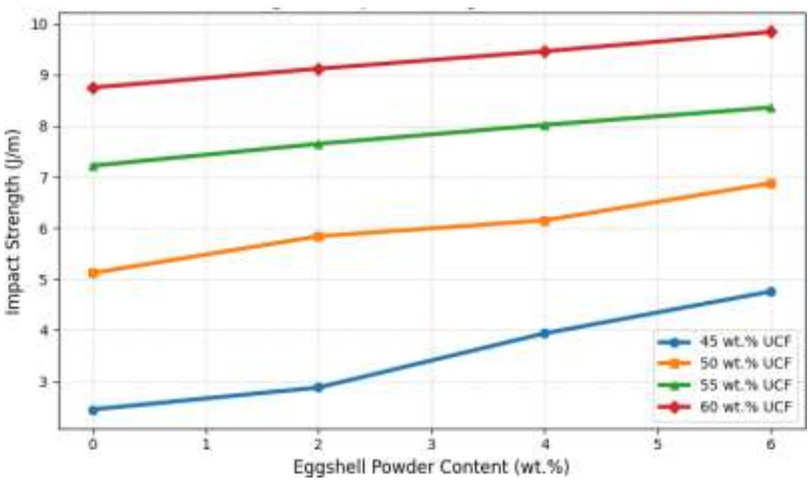
The randomly dispersed reinforcement fibers contributed toward uniform stress distribution throughout the composite structure. Simultaneously, the rigid eggshell particles increased matrix stiffness and reduced the possibility of localized deformation under bending loads. The flexural strength behavior is presented in Figure 4.2.

The incorporation of eggshell filler also contributed toward reduced porosity within the composite system. Lower porosity improves structural compactness and decreases the occurrence of micro-crack initiation points. Consequently, the developed composites exhibited superior bending resistance compared with filler-free polymer systems.

4.4 Impact Strength Characteristics

Impact strength analysis was performed to investigate the energy absorption capability of the fabricated sustainable composites under sudden loading conditions. The impact strength behavior of the fabricated composites is shown in Figure 4.3.

Fig.4.3 Impact Strength



The results demonstrated that eggshell filler addition considerably improved the impact resistance of the composite system. The enhancement in impact performance is mainly related to improved interfacial bonding and the ability of filler particles to distribute impact stresses uniformly throughout the polymer matrix.

The reinforcement fibers acted as crack arresters during impact loading and prevented sudden catastrophic failure. Simultaneously, the eggshell particles absorbed a portion of the externally applied energy and reduced stress concentration around fracture regions.

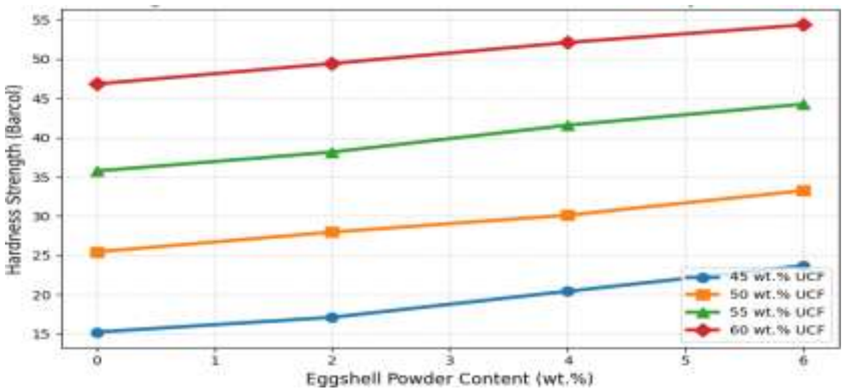
The filler particles also contributed toward minimizing void formation inside the composite structure. Reduced void content improves matrix compactness and prevents rapid crack propagation under impact conditions.

The developed sustainable composites therefore exhibited improved toughness and higher resistance against sudden fracture, indicating their suitability for lightweight structural and semi-structural applications.

4.5 Hardness Characteristics

Hardness analysis was conducted to evaluate the resistance of the fabricated composites against surface indentation and localized deformation. The hardness behavior of the developed composites is illustrated in Figure 4.4.

Fig.4.4 Hardness strength



The results indicate that the incorporation of eggshell powder significantly enhanced the hardness characteristics of the composite system. The rigid calcium carbonate-rich particles present in eggshell powder improved the compactness of the matrix structure and increased resistance against indenter penetration.

The dispersion of filler particles within the polymer matrix restricted localized plastic deformation and improved surface rigidity. Furthermore, better bonding between reinforcement fibers and matrix materials contributed toward enhanced load distribution during indentation testing.

The increase in hardness behavior demonstrates that sustainable waste-derived fillers can effectively improve surface mechanical performance while simultaneously supporting environmentally responsible waste reutilization.

4.6 Thermal Stability Analysis

Thermal stability evaluation was performed using thermogravimetric analysis to investigate the degradation behavior of the fabricated composites under elevated temperature conditions. The thermal analysis results demonstrated that filler-loaded composites exhibited improved thermal resistance compared with filler-free specimens. Initial mass loss observed at lower temperature ranges corresponded to the removal of absorbed moisture and volatile constituents. The major degradation stage occurred at elevated temperatures due to polymer matrix decomposition. However, the inclusion of eggshell filler delayed the thermal degradation process and improved composite stability.

The improved thermal resistance can be attributed to the presence of calcium carbonate-rich filler particles that act as thermal barriers and reduce heat transfer within the matrix system. The filler particles also restricted polymer chain mobility and delayed decomposition reactions.

The enhanced thermal behavior indicates that the fabricated sustainable composites can withstand moderate thermal environments and may be suitable for lightweight structural applications requiring improved heat resistance.

4.7 Morphological Investigation

Morphological evaluation was conducted to investigate the dispersion of reinforcement fibers and filler particles within the polymer matrix. The analysis revealed that cigarette filter fibers were distributed effectively throughout the matrix structure, enabling efficient stress transfer and improved mechanical behavior. Eggshell powder particles exhibited satisfactory compatibility with the polymer matrix and contributed toward enhanced interfacial bonding.

The fracture surface analysis also demonstrated reduced void formation and improved matrix compactness in filler-loaded composites. Strong interfacial adhesion prevented premature fiber pull-out and reduced crack propagation during mechanical loading conditions.
The improved morphological characteristics contributed significantly toward enhanced tensile, flexural, impact, and hardness properties observed during experimental investigation.

4.8 Environmental and Municipal Sustainability Implications

The experimental results demonstrate that problematic urban waste materials such as discarded cigarette filters and eggshell waste can be effectively transformed into sustainable engineering composites through environmentally responsible recycling strategies.

From a municipal governance perspective, the proposed waste reutilization framework offers several sustainability benefits, including:

1. Reduction of urban litter accumulation.
2. Diversion of cigarette and food waste from landfill sites.
3. Promotion of decentralized recycling systems.
4. Support for circular economy implementation.
5. Development of low-cost eco-friendly engineering materials.
6. Improvement of public environmental awareness.

Local self-government institutions can integrate such sustainable waste-to-resource initiatives into urban solid waste management policies through organized collection systems and community-level recycling programs.

The findings also highlight the potential for establishing small-scale municipal recycling industries capable of converting urban waste streams into commercially valuable products. Such initiatives may generate employment opportunities while simultaneously reducing environmental pollution associated with uncontrolled waste disposal.

4.9 Summary of Results

The results obtained from the present investigation confirm that recycled cigarette filter fibers and eggshell powder can be successfully utilized in sustainable composite fabrication. The incorporation of eggshell filler improved tensile strength, flexural behavior, impact resistance, hardness characteristics, and thermal stability of the developed composites.
The study further demonstrates that environmentally problematic municipal waste streams can be transformed into value-added engineering resources through sustainable local self-government strategies and circular economy-oriented waste management practices.
The overall findings establish that sustainable composite development using urban waste materials represents a promising approach for supporting environmental sustainability, municipal waste reduction, and decentralized recycling implementation.

5. CONCLUSION

The present investigation successfully established a circular urban waste governance framework for the development of hybrid biofiller composites using recycled municipal waste resources. The study demonstrated that discarded urban wastes can be effectively transformed into functional engineering materials through environmentally responsible recovery and manufacturing strategies. Cigarette filter fibers and eggshell powder were successfully incorporated within a polyvinyl ester matrix system to fabricate lightweight hybrid biofiller composites with enhanced structural and thermal characteristics.
Experimental evaluation confirmed that the incorporation of hybrid biofillers considerably

improved tensile strength, flexural behavior, impact resistance, surface hardness, and thermal stability of the fabricated composites. The improvement in composite performance was primarily attributed to enhanced interfacial adhesion, effective stress transfer mechanisms, reduced structural defects, and improved matrix compactness resulting from filler dispersion. Morphological analysis further indicated satisfactory bonding between reinforcement fibers, filler particles, and the polymer matrix, contributing toward improved mechanical reliability and crack resistance.

Beyond material development, the study emphasized the significance of integrating municipal waste recovery systems with circular economy implementation strategies. The proposed framework supports decentralized waste segregation, landfill reduction, resource-efficient recycling, and sustainable urban governance through community-level waste reutilization practices. The investigation highlights the potential role of local self-government institutions in promoting organized waste recovery networks capable of converting problematic urban waste streams into economically beneficial composite materials.

The overall findings confirm that hybrid biofiller composite technology offers a promising interdisciplinary approach for connecting sustainable materials engineering with municipal environmental governance. The proposed methodology contributes toward urban resource efficiency, environmental protection, and circular economy-driven development while supporting long-term sustainable municipal management practices.

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