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Engineering Performance Assessment of Composite Materials for Wastewater Treatment Plant Infrastructure Applications

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Abstract
The mechanical performance of polymer composite materials plays a critical role in determining their suitability for structural applications in aggressive wastewater treatment plant (WWTP) environments. This study experimentally investigated sixteen polymer composite formulations manufactured using epoxy and unsaturated polyester matrices reinforced with fiberglass, carbon fiber, polypropylene fiber, silicon dioxide (SiO_2), and aluminum oxide (Al_2O_3) micro- and nano-fillers. The mechanical characterization included tensile strength, Shore D hardness, and Izod impact resistance, which were evaluated according to ASTM D3039, ASTM D2240, and ASTM D256, respectively.
The experimental results demonstrated that both the polymer matrix and reinforcement architecture significantly influenced the mechanical behavior of the investigated composites. Fiber-reinforced composites exhibited substantially higher tensile strength than particulate-filled composites, with epoxy reinforced with carbon fiber achieving the maximum tensile strength of **28.66 MPa**, followed by epoxy reinforced with fiberglass (**27.81 MPa**). Fiberglass-reinforced polyester exhibited the highest impact resistance, while epoxy-based composites generally provided superior tensile strength and hardness because of their stronger matrix–reinforcement interaction and higher structural rigidity.
Overall, the findings indicate that continuous fiber reinforcement is more effective than particulate fillers in improving the mechanical performance of polymer composites. The generated experimental database provides valuable engineering information for selecting polymer composite materials intended for wastewater treatment plant infrastructure requiring high durability, mechanical reliability, and long-term structural performance under severe operating conditions.

Keywords: Wastewater treatment plants; Polymer composites; Mechanical properties; Tensile strength; Shore D hardness; Impact resistance; Epoxy resin; Polyester resin; Fiber reinforcement; Civil engineering.

1. Introduction

Wastewater treatment plants (WWTPs) are indispensable infrastructures for safeguarding public health and protecting aquatic ecosystems. Mechanical components operating within these facilities are continuously subjected to chemically aggressive wastewater, high humidity, suspended abrasive particles, and cyclic mechanical loading, which collectively accelerate material degradation and reduce service life. Among these components, fine screening units represent the first mechanical barrier in the treatment process and are particularly vulnerable to wear, impact, and corrosion. Their premature failure increases maintenance frequency, interrupts plant operation, and significantly raises lifecycle costs. Therefore, the development of durable engineering materials capable of sustaining long-term performance under harsh wastewater environments has become an important research objective in civil and environmental engineering (Metcalf & Eddy, 2014; Luo et al., 2022; Wang et al., 2023).

Fiber-reinforced polymer (FRP) composites have attracted considerable attention as alternatives to conventional metallic materials because of their excellent corrosion resistance, high specific strength, low density, and

reduced maintenance requirements. Their mechanical performance can be tailored by selecting appropriate polymer matrices and reinforcing phases, enabling the production of composite materials suitable for demanding engineering environments. Unsaturated polyester and epoxy resins remain the most commonly used thermosetting matrices due to their favorable processing characteristics, chemical stability, and excellent interfacial adhesion. Likewise, reinforcing systems such as glass fiber, carbon fiber, polypropylene fiber, silicon dioxide (SiO_2), and aluminum oxide (Al_2O_3) have been widely employed to improve the mechanical performance and durability of polymer composites (Kabir et al., 2022; Chen et al., 2024; Thomason, 2022).

The mechanical performance of polymer composites depends not only on the intrinsic properties of the reinforcing phase but also on filler dispersion, matrix–reinforcement interfacial bonding, curing conditions, and manufacturing quality. Consequently, evaluating a single mechanical property cannot accurately represent the overall engineering performance of a composite material. Instead, an integrated evaluation involving tensile strength, impact resistance, and surface hardness is required to provide a realistic assessment of structural behavior under practical service conditions (Fiore et al., 2021; Zhang et al., 2023; Li et al., 2023).

Although extensive research has been conducted on polymer composite materials, previous investigations have generally focused on individual reinforcement systems or isolated mechanical properties. In addition, most reported studies investigated a limited number of composite formulations, making direct comparison among different reinforcing materials difficult. More importantly, only a limited number of studies have combined comprehensive experimental characterization with computational multi-criteria evaluation to support engineering material selection for wastewater treatment applications. Consequently, the combined influence of tensile strength, impact resistance, hardness, engineering applicability, and practical performance has not been comprehensively evaluated within a unified decision-support framework.

The novelty of the present study lies in the development of an integrated experimental–computational methodology for selecting locally manufactured polymer composites intended for wastewater treatment plant applications. Sixteen composite formulations based on unsaturated polyester and epoxy matrices reinforced with various fibers and ceramic fillers were fabricated and experimentally characterized through tensile, Shore D hardness, and impact resistance testing. Subsequently, the experimental results were incorporated into a MATLAB-based multi-criteria decision analysis (MCDA) framework to establish an objective engineering ranking of the investigated materials. Unlike conventional approaches that rely on individual mechanical properties, the proposed methodology simultaneously evaluates multiple engineering criteria to identify the most suitable composite material for fine screening units operating under aggressive wastewater conditions.

Therefore, the objectives of this study were to **(i)** fabricate sixteen polyester- and epoxy-based composite formulations reinforced with different fibers and ceramic fillers, **(ii)** experimentally evaluate their tensile strength, impact resistance, and Shore D hardness, **(iii)** develop a MATLAB-based computational framework for integrated material ranking, and **(iv)** identify the optimum locally manufactured composite material suitable for wastewater treatment plant fine screening applications based on comprehensive engineering performance.

2. Materials and Experimental Program

2.1 Materials

Sixteen polymer composite formulations were manufactured and experimentally evaluated in this study to investigate their suitability for structural applications in wastewater treatment plant (WWTP) infrastructure. Two thermosetting polymer matrices, namely epoxy resin and unsaturated polyester resin, were selected because they represent the two most widely used thermosetting polymers in structural polymer composites owing to their excellent corrosion resistance, dimensional stability, processability, and long-term durability under aggressive wastewater environments.

Different reinforcement systems were incorporated into the polymer matrices to improve their mechanical behavior. Continuous fiber reinforcements included fiberglass and carbon fiber, while particulate reinforcements consisted of nano- and micro-sized silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3). Polypropylene fibers were also incorporated as short-fiber reinforcement to enhance toughness and crack resistance. In addition, unreinforced epoxy and polyester specimens were prepared to serve as reference materials for evaluating the influence of reinforcement on mechanical performance.

A total of sixteen composite formulations were fabricated using identical manufacturing procedures to ensure consistency throughout the experimental program. The investigated materials are presented in Table 1.

Table 1. Polymer composite materials investigated in the present study.

Sample No.	Material Code	Composite Material
1	P-CF	Polyester + Carbon Fiber
2	P-SiO_2 Nano	Polyester + SiO_2 Nano
3	P-SiO_2 Micro	Polyester + SiO_2 Micro
4	P-Al_2O_3 Micro	Polyester + Al_2O_3 Micro
5	P-Al_2O_3 Nano	Polyester + Al_2O_3 Nano
6	P-PP	Polyester + Polypropylene Fiber
7	P-FG	Polyester + Fiberglass
8	P-Original	Polyester Resin (Neat Polyester)
9	E-CF	Epoxy + Carbon Fiber
10	E-PP	Epoxy + Polypropylene Fiber
11	E-Original	Epoxy Resin (Neat Epoxy)
12	E-SiO_2 Micro	Epoxy + SiO_2 Micro
13	E-Al_2O_3 Nano	Epoxy + Al_2O_3 Nano
14	E-SiO_2 Nano	Epoxy + SiO_2 Nano
15	E-FG	Epoxy + Fiberglass
16	E-Al_2O_3 Micro	Epoxy + Al_2O_3 Micro

The investigated composite formulations were selected to represent a wide range of reinforcing mechanisms commonly employed in polymer composite technology. This experimental matrix enabled systematic evaluation of the influence of reinforcement type, reinforcement size, and polymer matrix on tensile strength, hardness, and impact resistance. This experimental design enabled direct comparison of the influence of polymer matrix, reinforcement type, and filler size on the overall mechanical performance of the investigated composites, thereby establishing a reliable engineering database for material selection in wastewater treatment applications.

2.2 Composite Fabrication

The polymer composite specimens were fabricated using a Manual Casting Techniquetechnique under controlled laboratory conditions. Two thermosetting polymer matrices, namely unsaturated polyester resin and epoxy resin, were employed as the primary matrix materials. Seven different reinforcing materials and fillers, including carbon fiber (CF), glass fiber (GF), polypropylene fiber (PPF), silicon dioxide nanoparticles (SiO_2), silicon dioxide microparticles (SiO_2), aluminum oxide nanoparticles (Al_2O_3), and aluminum oxide microparticles (Al_2O_3), were incorporated separately into the polymer matrices. Each reinforcing material was added at a fixed concentration of **5 wt.%**based on the resin weight.

Initially, the required quantity of polyester or epoxy resin was accurately weighed using a digital laboratory balance. The selected reinforcement or filler was subsequently added to the resin and manually mixed until a homogeneous dispersion was achieved.The mixture was manually stirred for approximately 3–5 min until visual homogeneity was achieved. Following complete homogenization, the appropriate curing agent was introduced according to the manufacturer's recommended mixing ratio. For the polyester system, methyl ethyl ketone peroxide (MEKP) was used as the curing agent, whereas the epoxy system was mixed with its corresponding amine-based hardener. The mixtures were continuously stirred to ensure uniform distribution of both the reinforcing phase and the curing agent throughout the polymer matrix.

After mixing, the prepared composite mixture was allowed to stand briefly to facilitate the escape of entrapped air bubbles. To further minimize internal voids, the mixture was subjected to a short thermal treatment at approximately **60 °C** before being poured into custom-fabricated silicone molds supported by rigid plaster holders. After casting, the mold surface was gently leveled, covered, and subjected to a compressive load to reduce any remaining air pockets and improve dimensional accuracy.

(**Source:** Photograph taken by the authors during the experimental work.)



Figure 1. Schematic illustration of the fabrication process of the investigated polymer composite specimen: (a) weighing of the raw materials, (b) mixing of the epoxy resin and hardener, (c) preparation of the silicone mold, (d) casting of the composite mixture into the prepared mold, (e) removal of the cured specimen from the mold (demolding), and (f) the final fabricated polymer composite specimen ready for machining and mechanical characterization.

The polyester-based composites were allowed to cure at room temperature for approximately **24 h**, whereas the epoxy-based composites were cured under identical laboratory conditions for approximately **48 h**. Following complete demolding, all fabricated specimens underwent a post-curing treatment at **80 °C** to complete the cross-linking reaction and ensure maximum polymerization before specimen preparation and mechanical testing.

Using this fabrication procedure, sixteen composite formulations together with the corresponding neat polyester and neat epoxy specimens were successfully produced. All specimens were subsequently machined into the required dimensions according to the corresponding ASTM standards for tensile, impact, and Shore D hardness testing.The complete fabrication procedure adopted in the present investigation is illustrated in Figure 2**.**

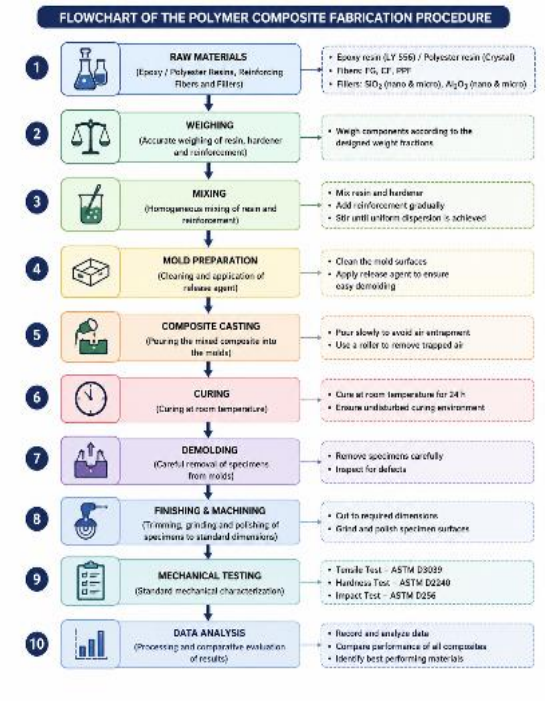


Figure 2. Flowchart of the polymer composite fabrication procedure.

Figure 2 The adopted fabrication methodology ensured specimen uniformity, minimized manufacturing variability, and guaranteed identical processing conditions for all investigated formulations. Consequently, the measured differences in mechanical behavior can be primarily attributed to the influence of reinforcement type rather than manufacturing inconsistencies.

The experimental program consisted of sixteen composite formulations prepared using two polymer matrices and seven different reinforcement systems. Each formulation was subjected to tensile, Shore D hardness, and Charpy impact testing following the corresponding ASTM standards. The obtained experimental data were subsequently processed using MATLAB for engineering ranking and material selection.

2.3 Mechanical Testing

The mechanical performance of the fabricated polymer composite specimens was experimentally evaluated through tensile strength, Shore D hardness, and impact resistance tests. All specimens were prepared according to the corresponding ASTM standards and tested under identical laboratory conditions to ensure experimental consistency, measurement reliability, and repeatability. The selected mechanical properties represent the primary engineering parameters governing the structural performance of polymer composites intended for wastewater treatment plant (WWTP) applications, where components are continuously exposed to mechanical loading, abrasive particles, and chemically aggressive environments

2.3.1 Tensile Test

The tensile behavior of the fabricated polymer composite specimens was evaluated using a **Universal Testing Machine (UTM)** in accordance with **ASTM D3039/D3039M-21**. Tensile loading was applied under displacement-controlled conditions until complete specimen failure, and the maximum tensile strength was automatically recorded by the testing system. Tensile strength was selected as the primary indicator of the load-carrying capacity and structural integrity of the investigated composites under static loading conditions.

The tensile test provides valuable information regarding the efficiency of stress transfer between the polymer matrix and the reinforcing phase. Consequently, the obtained results were used to evaluate the influence of different reinforcement systems on the structural performance of polyester- and epoxy-based composite materials intended for wastewater treatment infrastructure.



Figure 3. Universal Testing Machine (UTM) used for tensile testing according to ASTM D3039/D3039M.

2.3.2 Hardness Test

Surface hardness was determined using the **Shore D hardness method** in accordance with **ASTM D2240-21**. Several measurements were obtained from different locations on each specimen to minimize local variations caused by material heterogeneity, and the arithmetic mean was considered the representative hardness value of each composite formulation.Shore D hardness was selected because it reflects the resistance of polymer composites to localized surface deformation and indentation. This property is particularly important for wastewater treatment components continuously exposed to abrasive suspended solids, frictional wear, and repeated mechanical contact. Therefore, hardness measurements provide an important engineering indicator of the expected surface durability of the investigated composite materials.



Figure 4. Shore D hardness tester used for hardness measurements according to ASTM D2240.

2.3.3 Impact Test

The impact resistance of the fabricated polymer composites was evaluated using the **Izod impact test** in accordance with **ASTM D256-20**. The absorbed impact energy was measured for each specimen and subsequently expressed as impact resistance (kJ/m²). This parameter was adopted to assess the capability of the investigated composites to absorb sudden mechanical energy without catastrophic fracture.Impact resistance represents an essential engineering property for polymer composite components operating in wastewater treatment plants, where accidental impacts, vibration, cyclic loading, and operational shocks may occur during long-term service. Therefore, the obtained impact values provide an important indication of the toughness and structural reliability of the investigated composite formulations under practical operating conditions.

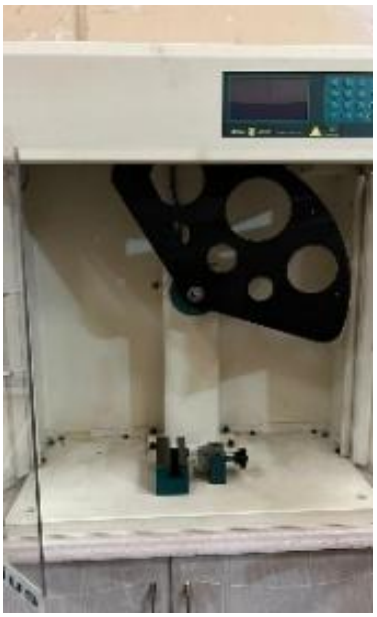


Figure 5. Izod impact testing machine used for determining the impact resistance of the investigated polymer composite specimens according to ASTM D256.

2.3.4 Experimental Repeatability

To ensure the reliability and repeatability of the experimental measurements, all mechanical tests were performed under identical laboratory conditions using standardized specimen geometries and testing procedures specified by the corresponding ASTM standards. For the Shore D hardness test, multiple measurements were obtained from different locations on each specimen and averaged to minimize local material heterogeneity. The experimental methodology adopted in the present investigation ensured consistent comparison among the sixteen investigated composite formulations

3. Results and Discussion

3.1 Tensile Strength

The tensile strength results of the sixteen fabricated polymer composite formulations are presented in **Table 2** and **Figure 6**. A clear variation in tensile behavior was observed among the investigated composites, reflecting the combined influence of polymer matrix characteristics, reinforcement type, reinforcement geometry, and matrix–reinforcement interfacial adhesion. These factors collectively govern stress transfer efficiency and ultimately determine the structural performance of polymer composites intended for wastewater treatment plant applications.

The highest tensile strength was recorded for **epoxy reinforced with carbon fiber (E-CF)**, which achieved **28.66 MPa**, followed closely by **epoxy reinforced with fiberglass (E-FG)** with **27.81 MPa**. The superior performance of these materials can be attributed to the high stiffness and excellent stress-transfer capability provided by continuous fiber reinforcement, allowing external loads to be efficiently distributed throughout the polymer matrix. In addition, the strong interfacial bonding between the epoxy matrix and reinforcing fibers delays crack initiation and propagation, The superior tensile performance of the carbon fiber composite is primarily attributed to the exceptionally high elastic modulus and tensile stiffness of carbon fibers, which efficiently transferred the applied load from the polymer matrix to the reinforcing phase. In addition, the continuous fiber architecture promoted crack bridging and delayed crack propagation, resulting in improved structural integrity during tensile loading.

thereby improving tensile performance. These findings agree with previous investigations demonstrating that continuous fibers significantly enhance the tensile behavior of thermosetting polymer composites (Mallick, 2007; Callister and Rethwisch, 2020).

Among the particulate-reinforced composites, epoxy specimens generally exhibited higher tensile strength than their polyester counterparts. This behavior can also be explained by the higher cross-link density of the epoxy network compared with unsaturated polyester. The stronger molecular structure of epoxy improves interfacial bonding with inorganic fillers and reduces stress concentration around filler particles, thereby enhancing the tensile load transfer efficiency.

Epoxy composites reinforced with micro-sized silica (E-SiO_2 Micro) and nano-sized silica (E-SiO_2 Nano) achieved tensile strengths of **21.82 MPa** and **21.14 MPa**, respectively, whereas polyester composites containing similar fillers exhibited considerably lower tensile performance. This behavior may be associated with the superior adhesion characteristics of the epoxy matrix, resulting in improved stress transfer between the polymer matrix and the reinforcing particles.

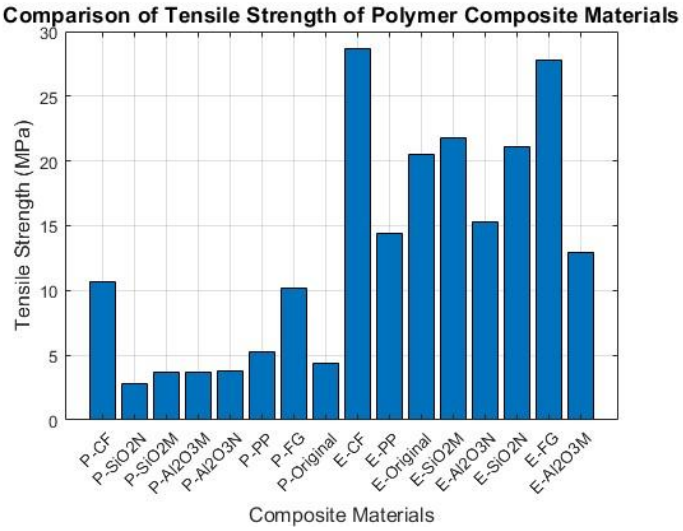
Polyester composites reinforced with fiberglass (P-FG) also demonstrated noticeable improvement compared with the remaining polyester formulations, achieving a tensile strength of **10.20 MPa**. In contrast, polyester composites reinforced with silicon dioxide and aluminum oxide particles exhibited relatively lower tensile strength, indicating that particulate reinforcement alone was less effective in improving tensile performance than continuous fiber reinforcement. Although fiberglass significantly improved the tensile behavior of polyester composites, its performance remained considerably lower than that of the corresponding epoxy-based formulation. This difference suggests that matrix characteristics play a critical role in determining the efficiency of fiber reinforcement, even when identical reinforcing fibers are employed.

The reference materials also exhibited different mechanical behavior. The unreinforced epoxy resin achieved a tensile strength of **20.53 MPa**, whereas the unreinforced polyester resin recorded only **4.33 MPa**. This considerable difference reflects the inherently higher mechanical capability of the epoxy matrix compared with the polyester matrix under identical testing conditions. The approximately five-fold increase in tensile strength observed for neat epoxy compared with neat polyester further confirms the superior mechanical capability of epoxy resin, which has been widely reported in structural polymer composite applications.Overall, the experimental results indicate that fiber reinforcement had a greater influence on tensile performance than particulate reinforcement, while epoxy-based composites consistently outperformed polyester-based composites. These observations suggest that continuous fiber reinforcement, particularly fiberglass and carbon fiber, provides the most effective strengthening mechanism for polymer composite materials intended for wastewater treatment plant infrastructure exposed to repeated mechanical loading and aggressive environmental conditions.

Comparison with Previous Studies

The present findings are consistent with those reported by Fiore et al. (2021), who demonstrated that continuous fiber reinforcement significantly improves the tensile behavior of thermosetting polymer composites through enhanced stress transfer mechanisms. Similar observations were reported by Kabir et al. (2022) and Chen et al. (2024), who found that epoxy-based composites generally exhibit superior tensile performance compared with polyester systems because of stronger matrix–fiber adhesion and higher cross-link density. The agreement between the present experimental observations and previously published investigations further confirms the reliability of the developed composite formulations.

Overall, the tensile test results demonstrate that reinforcement architecture exerts a greater influence on tensile performance than filler particle size. Continuous fiber reinforcements, particularly carbon fiber and fiberglass, provided the most efficient strengthening mechanisms, while the epoxy matrix consistently exhibited superior structural performance owing to its stronger interfacial adhesion and higher load transfer capability. These findings indicate that epoxy-based fiber-reinforced composites represent the most promising candidates for structural components operating under severe mechanical loading in wastewater treatment facilities



The tensile strength distribution presented in **Figure 6** clearly illustrates the substantial improvement achieved through continuous fiber reinforcement compared with particulate fillers. The observed trend confirms that reinforcement geometry has a greater influence on tensile behavior than filler particle size, highlighting the dominant role of efficient stress transfer in determining structural performance

3.2 Hardness Performance

The Shore D hardness results of the investigated polymer composite formulations are summarized in **Table 3** and presented in **Figure 7**. The experimental results revealed noticeable differences in surface hardness among the fabricated composites, indicating that both the polymer matrix and the reinforcement architecture significantly affected the resistance of the materials to localized plastic deformation. Surface hardness is an important engineering parameter for wastewater treatment components because it is directly associated with abrasion resistance, wear behavior, and long-term durability under aggressive operating conditions.

Among all investigated formulations, **polyester reinforced with fiberglass (P-FG)** exhibited the highest Shore D hardness value (**42.9**), followed closely by **epoxy reinforced with fiberglass (E-FG)** (**39.2**) and **neat epoxy resin** (**36.1**). The superior hardness of fiberglass-reinforced composites can be attributed to the high elastic modulus and rigidity of continuous glass fibers, which effectively restrict localized deformation of the surrounding polymer matrix during indentation. Furthermore, the efficient load transfer between the matrix and the reinforcing fibers contributes to improved surface stiffness and higher resistance to permanent indentation.

In contrast, the **neat polyester resin** exhibited the lowest hardness value (**18.1**), reflecting the relatively lower stiffness and cross-link density of the polyester matrix compared with epoxy-based systems. Although ceramic fillers such as **SiO_2** and **Al_2O_3** improved surface hardness to varying degrees, their contribution remained lower than that achieved by continuous fiberglass reinforcement. This behavior suggests that the effectiveness of particulate fillers is primarily governed by particle dispersion and matrix–particle interfacial adhesion, whereas

continuous fibers provide a more efficient reinforcing mechanism through continuous load transfer and deformation restraint.

The present findings are consistent with previous investigations reporting that continuous glass fiber reinforcement significantly enhances the surface hardness of thermosetting polymer composites owing to its high stiffness and excellent interfacial bonding with polymer matrices (Fiore et al., 2021; Kabir et al., 2022; Chen et al., 2024). Similar improvements in hardness have also been reported for epoxy-based composites reinforced with inorganic fillers, although their effectiveness strongly depends on filler size, dispersion quality, and particle distribution within the polymer matrix.

Overall, the hardness results demonstrate that both the polymer matrix and reinforcement type play decisive roles in determining the surface mechanical performance of polymer composites. Continuous fiberglass reinforcement produced the highest resistance to localized deformation, while epoxy-based composites generally exhibited superior hardness compared with polyester systems. These observations indicate that fiberglass-reinforced polymer composites possess enhanced surface durability and are therefore promising candidates for wastewater treatment plant components subjected to continuous abrasion, friction, and mechanical contact.

Comparison with Previous Studies

The hardness results obtained in the present investigation are in good agreement with previously published studies on fiber-reinforced thermosetting polymer composites. **Fiore et al. (2021)** reported that continuous glass fiber reinforcement significantly increases the surface hardness of polyester composites by restricting localized matrix deformation and improving stress distribution during indentation. Similarly, **Kabir et al. (2022)** demonstrated that epoxy-based composites generally exhibit higher hardness than polyester systems owing to their greater cross-link density and stronger matrix–reinforcement interfacial bonding. Furthermore, **Chen et al. (2024)** concluded that although ceramic fillers such as SiO_2 and Al_2O_3 contribute to hardness enhancement, their effectiveness strongly depends on particle dispersion and interfacial compatibility with the polymer matrix. The experimental observations of the present study are consistent with these findings, confirming that continuous fiberglass reinforcement provides the most effective mechanism for improving surface hardness, while epoxy matrices generally exhibit superior resistance to localized deformation compared with polyester matrices. These results further validate the suitability of fiberglass-reinforced epoxy and polyester composites for structural components operating under abrasive wastewater treatment environments

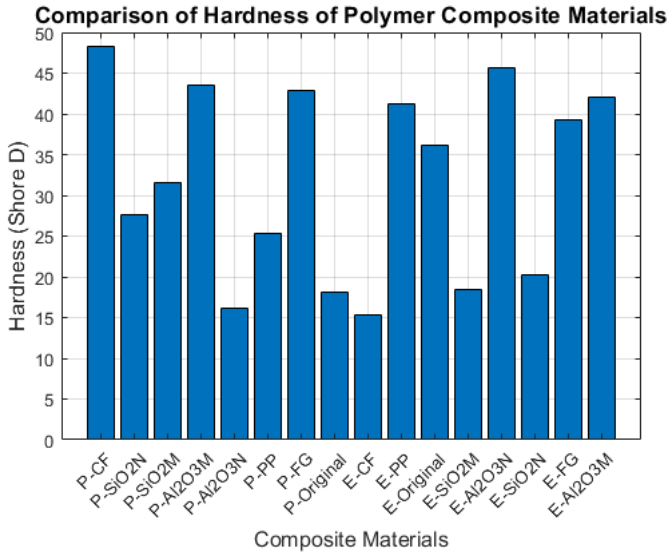


Figure 7. Comparison of Shore D hardness of the investigated polymer composite materials.

Figure 7 illustrates the Shore D hardness distribution of the sixteen investigated composite formulations. A clear improvement in hardness can be observed for fiberglass-reinforced composites compared with particulate-filled systems, confirming the dominant role of continuous fiber reinforcement in increasing surface stiffness. The figure also demonstrates that epoxy-based formulations generally achieved higher hardness than polyester-based composites, reflecting the superior rigidity and cross-link density of the epoxy matrix. These results

further support the suitability of fiberglass-reinforced polymer composites for engineering applications requiring high wear resistance and long-term dimensional stability

3.3 Impact Resistance

The impact resistance results of the sixteen fabricated polymer composite formulations are summarized in **Table 4** and presented in **Figure 8**. Significant differences were observed in the impact behavior of the investigated composites, demonstrating that both the polymer matrix and the reinforcement architecture strongly influenced the ability of the materials to absorb impact energy and resist sudden fracture. Impact resistance represents a critical engineering property for wastewater treatment components subjected to accidental impacts, vibration, and repeated mechanical shocks during long-term service.

Among all investigated formulations, **polyester reinforced with fiberglass (P-FG)** exhibited the highest impact resistance (**7.006 kJ/m²**), followed by **epoxy reinforced with fiberglass (E-FG)** (**2.221 kJ/m²**). The outstanding performance of fiberglass-reinforced composites can be attributed to the continuous fiber architecture, which effectively redistributes impact stresses, bridges developing cracks, and delays crack propagation throughout the polymer matrix. These mechanisms substantially increase the amount of energy absorbed before final failure, thereby improving the overall toughness of the composite.

The **P-Original** specimen also exhibited relatively high impact resistance (**2.205 kJ/m²**), whereas **E-Original** recorded the lowest value (**0.573 kJ/m²**), reflecting the comparatively brittle nature of unreinforced epoxy under dynamic loading. Although epoxy generally provides superior tensile strength because of its highly cross-linked molecular structure, its limited ductility reduces its capacity to dissipate impact energy unless reinforced with continuous fibers. Consequently, fiber reinforcement plays a more significant role in improving impact toughness than in enhancing tensile performance alone.

In contrast, composites reinforced with **SiO_2** and **Al_2O_3** particles generally exhibited lower impact resistance than fiber-reinforced formulations. This behavior is primarily associated with the rigid nature of ceramic particles, which may act as local stress concentration sites during sudden loading if crack-bridging mechanisms are absent. Unlike continuous fibers, particulate reinforcements possess limited ability to arrest crack propagation or absorb impact energy through fiber pull-out and progressive failure mechanisms.

Overall, the obtained results demonstrate that reinforcement architecture is the dominant factor governing the impact performance of polymer composites. Continuous fiberglass reinforcement provided the highest improvement in impact toughness, whereas ceramic fillers produced only moderate enhancement. These observations indicate that fiberglass-reinforced polymer composites are the most promising candidates for wastewater treatment plant screening components subjected to repeated impact loading and severe operating conditions.

Comparison with Previous Studies

The impact resistance results obtained in the present study are consistent with previously published investigations on fiber-reinforced thermosetting polymer composites. **Fiore et al. (2021)** reported that continuous glass fiber reinforcement substantially increases impact toughness by promoting crack bridging and progressive energy dissipation during fracture. Similarly, **Kabir et al. (2022)** demonstrated that epoxy composites require continuous fiber reinforcement to overcome the inherent brittleness of the epoxy matrix under dynamic loading. Furthermore, **Chen et al. (2024)** observed that ceramic fillers improve stiffness and hardness but contribute less effectively to impact energy absorption because of their rigid nature and limited crack-arrest capability. The agreement between the present results and previous studies confirms that continuous fiberglass reinforcement remains one of the most efficient strengthening mechanisms for improving the impact performance of thermosetting polymer composites intended for harsh engineering environments.

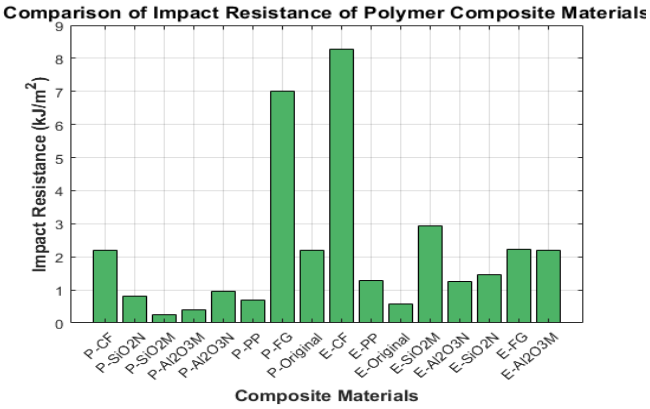


Figure 8. Comparison of impact resistance of the investigated polymer composite materials.

Figure 8illustrates the impact resistance distribution of the investigated composite formulations. The results clearly demonstrate the superior energy absorption capability of fiberglass-reinforced composites compared with particle-filled systems. In addition, epoxy-based composites exhibited a pronounced improvement in impact resistance only after continuous fiber reinforcement, highlighting the importance of reinforcement architecture in controlling fracture behavior under dynamic loading.

3.4 Comparative Mechanical Performance

The experimental results demonstrated that the mechanical performance of the investigated polymer composite materials was governed primarily by both the polymer matrix and the reinforcement architecture. Considerable differences were observed among the sixteen investigated formulations, indicating that each reinforcement system contributed differently to tensile strength, hardness, and impact resistance.Fiber-reinforced composites consistently outperformed particulate-filled composites in tensile strength owing to the efficient stress-transfer capability of continuous fibers. Carbon fiber reinforcement produced the highest tensile performance, whereas fiberglass reinforcement provided the most balanced combination of tensile strength, surface hardness, and impact resistance. These findings confirm that continuous fibers remain the most effective reinforcement system for structural polymer composites operating under aggressive service environments.

Conversely, ceramic fillers such as silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) primarily enhanced surface rigidity rather than overall structural performance. Although these fillers improved hardness to varying degrees, their contribution to tensile strength and impact resistance remained lower than that achieved by continuous fiber reinforcement. This behavior can be attributed to the localized strengthening effect of rigid particles, whereas continuous fibers provide efficient stress transfer, crack bridging, and energy dissipation mechanisms during mechanical loading.

Comparison between the two polymer matrices further revealed that epoxy-based composites generally exhibited superior tensile strength and hardness compared with polyester-based composites. This behavior is associated with the higher cross-link density and stronger matrix–reinforcement interfacial adhesion characteristic of epoxy systems. In contrast, fiberglass-reinforced polyester composites exhibited considerably greater impact resistance, indicating superior energy absorption capability under dynamic loading conditions.From an engineering perspective, no single composite formulation simultaneously achieved the highest values for all investigated mechanical properties. Therefore, material selection for wastewater treatment plant applications should be based on the specific service requirements rather than a single performance criterion. Components primarily subjected to static loading would benefit from carbon-fiber-reinforced epoxy composites, whereas fine screening units exposed to repeated impact loading and abrasive conditions may benefit from fiberglass-reinforced polyester composites because of their balanced mechanical performance.

Overall, the comparative evaluation demonstrates that **reinforcement architecture exerts a greater influence on composite performance than filler particle size**. The generated experimental database provides a reliable engineering foundation for selecting locally manufactured polymer composite materials suitable for wastewater treatment infrastructure.

Comparison with Previous Studies

The overall mechanical trends observed in the present study are consistent with previously published investigations on thermosetting polymer composites. Continuous fiber reinforcement has been widely reported to provide superior improvements in tensile strength and impact resistance compared with particulate fillers because of its higher stress-transfer efficiency and crack-bridging capability. Similarly, previous studies have demonstrated that epoxy-based composites generally exhibit higher tensile strength and hardness than polyester systems owing to their stronger interfacial bonding and higher cross-link density, whereas fiberglass reinforcement offers a more balanced combination of strength, toughness, and durability. The agreement between the present findings and previous investigations confirms that reinforcement architecture is the governing factor controlling the mechanical performance of polymer composites intended for structural engineering applications.

3.5 Engineering Implications for Wastewater Treatment Plant Applications

The experimental findings demonstrate that the selection of polymer composite materials for wastewater treatment plant (WWTP) applications should be based on a comprehensive engineering evaluation rather than on a single mechanical property. Since structural components operating in aggressive wastewater environments are simultaneously subjected to static loading, impact forces, abrasive wear, and chemical exposure, an integrated assessment of tensile strength, surface hardness, and impact resistance is essential to ensure reliable long-term performance.The obtained results indicate that **epoxy-based composites**, particularly those reinforced with continuous fibers, are more suitable for structural components primarily subjected to static mechanical loading owing to their superior tensile strength, higher stiffness, and improved surface hardness. In contrast, **fiberglass-reinforced polyester composites** exhibited outstanding impact resistance, making them more appropriate for components exposed to repeated mechanical shocks, vibration, and dynamic loading during wastewater treatment operations.

From a practical engineering perspective, **fiberglass-reinforced polymer composites** provided the most balanced overall mechanical performance among the investigated formulations. In addition to their satisfactory tensile strength, these composites exhibited enhanced hardness and exceptional impact resistance while maintaining relatively simple fabrication procedures and favorable economic feasibility. Furthermore, their excellent corrosion resistance and low maintenance requirements make them attractive alternatives to conventional metallic materials commonly used in wastewater treatment facilities.The present findings also demonstrate that **reinforcement architecture has a greater influence on composite performance than filler particle size**. Continuous fiber reinforcement significantly improved stress transfer, crack-bridging capability, and energy absorption, whereas ceramic fillers mainly enhanced localized surface rigidity without providing comparable improvements in structural load-bearing capacity. Therefore, the selection of reinforcement type should be based on the expected service conditions of the structural component rather than on individual mechanical properties alone.

Overall, the developed experimental database provides practical engineering guidance for selecting durable, locally manufactured polymer composites suitable for the rehabilitation and replacement of fine screening units operating under aggressive wastewater environments. Moreover, the proposed experimental methodology can serve as a decision-support framework for future material selection and sustainable infrastructure development in wastewater treatment facilities.The integration of standardized mechanical characterization with engineering performance assessment provides a practical basis for future optimization of polymer composite materials intended for wastewater treatment infrastructure. This approach facilitates objective material selection based on multiple performance criteria and supports the development of more durable and sustainable engineering solutions.



Figure 9. Installation of the replacement composite component in the Fine Screening Unit



Figure 10. Location and installation position of the investigated component within the Fine Screening Unit.



Figure 11.Conduct a field examination of the manufactured part that was examined and installed inside the precision sorting unit by the researcher.

4. Conclusions

This study experimentally investigated the mechanical performance of sixteen polymer composite formulations fabricated using epoxy and unsaturated polyester matrices reinforced with various continuous fibers and ceramic fillers for potential application in wastewater treatment plant (WWTP) infrastructure. Tensile strength, Shore D hardness, and impact resistance were systematically evaluated to identify composite materials capable of withstanding the severe mechanical and environmental conditions associated with fine screening units.The experimental results confirmed that reinforcement architecture is the governing factor controlling the mechanical performance of thermosetting polymer composites. Continuous fiber reinforcement produced substantially greater improvements than particulate fillers, particularly in tensile strength and impact resistance. Among all investigated formulations, epoxy reinforced with carbon fiber (E-CF) exhibited the highest tensile strength, whereas polyester reinforced with fiberglass (P-FG) demonstrated the greatest impact resistance. In addition, fiberglass-reinforced composites provided the most balanced overall mechanical performance by simultaneously enhancing tensile behavior, surface hardness, and impact toughness.

The comparison between the two polymer matrices revealed that epoxy-based composites generally exhibited superior tensile strength and hardness because of their higher cross-link density and stronger matrix–reinforcement interfacial bonding. Conversely, polyester-based composites showed greater impact energy absorption, especially when reinforced with continuous fiberglass, making them more suitable for applications involving repeated dynamic loading and mechanical shocks.The findings further demonstrate that material selection for wastewater treatment applications should be based on a multi-criteria engineering assessment rather than on a single mechanical property. The generated experimental database provides practical guidance for selecting locally manufactured polymer composites capable of replacing conventional metallic materials in corrosive wastewater environments.

The principal contribution of this study lies in establishing a comprehensive experimental database for sixteen locally manufactured polymer composite formulations and providing an engineering basis for selecting durable composite materials for wastewater treatment infrastructure. The proposed methodology can support future optimization of polymer composite systems and contribute to the development of more sustainable, corrosion-resistant, and mechanically reliable civil engineering materials.Furthermore, the generated experimental data provide a reliable foundation for future computational material-selection models and multi-criteria optimization techniques aimed at improving the design and rehabilitation of wastewater treatment infrastructure.

5. Future Work

Future research should focus on evaluating the long-term durability of the selected polymer composite materials under actual wastewater treatment plant (WWTP) operating conditions. Particular attention should be given to accelerated aging, chemical corrosion resistance, ultraviolet (UV) weathering, fatigue performance, creep behavior, and long-term environmental degradation to better simulate real service conditions.In addition, advanced numerical approaches, including **finite element analysis (FEA)** and computational simulations, should be integrated with the experimental results to predict the structural response and failure mechanisms of polymer composite screening components subjected to combined mechanical and environmental loading.Further studies are also recommended to investigate the influence of different reinforcement contents, hybrid reinforcement systems, and alternative nanoparticle combinations in order to optimize the overall mechanical performance of polymer composites. Finally, comprehensive **life-cycle assessment (LCA)** together with techno-economic analysis should be performed to evaluate the long-term sustainability, maintenance requirements, and economic feasibility of implementing these locally manufactured composite materials in full-scale wastewater treatment infrastructure.Moreover, the experimental database generated in the present study can serve as a benchmark for future data-driven optimization and artificial intelligence (AI)-assisted material selection techniques aimed at developing next-generation sustainable polymer composites for wastewater treatment applications

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8. Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this work.

9. Data Availability Statement

The experimental data supporting the findings of this study are available from the corresponding author upon reasonable request.

10. Author Contributions

Marwa Jabbar Hasan: Conceptualization, experimental design, composite fabrication, laboratory testing, data collection, data analysis, interpretation of results, manuscript preparation, and original draft writing.

Prof. Dr. Hamid Reza Rabie Far: Research supervision, methodology development, scientific guidance, critical review of experimental results, manuscript revision, and final approval of the submitted version.

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