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Effects of the Binder Type on the Microstructure and Mechanical Properties of Reinforced Plastic Composites

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Abstract

This study investigated the effect of binder type and its interaction with PET, PVC, and banana fibre in the production of reinforced plastic composites aimed at promoting environmental conservation through sustainable material alternatives. The objective was to evaluate how epoxy and polyester binders influence the mechanical and microstructural properties of the composites. Samples were fabricated using the hand lay-up method, followed by microstructural analysis using scanning electron microscopy (SEM) and mechanical testing using a universal testing machine for tensile, compression, and flexural properties. The results showed that binder type significantly affected both mechanical performance and microstructure, with polyester-based composites demonstrating improved interfacial bonding and superior mechanical properties compared to epoxy-based composites. It is recommended that further research be conducted to explore additional binder types and optimize processing techniques to further enhance composite performance and broaden their application in sustainable materials.

Keywords:

Sustainability, Natural fibres, Banana fibres, binder, Mechanical testing, Scanning electron microscope.

1. Introduction

Banana fibres, a natural and biodegradable resource, offer a promising solution due to their excellent mechanical properties, low cost, and widespread availability. The increasing demand for sustainable materials in engineering applications has led to a growing interest in natural fibres-reinforced composites (Soni et al., 2024). However, the application of banana fibres in

plastic composites remains underexplored, with gaps in understanding their performance under varying conditions, such as fibres-matrix compatibility, moisture sensitivity, and inconsistent mechanical behaviour are challenges that need to be systematically addressed to fully realize their potential (Atmakuri et al., 2025).

Banana fibre-reinforced plastic composites offer a promising solution to address environmental and material performance challenges. These composites combine natural fibres with a polymer matrix to create materials with enhanced microstructural and mechanical properties, suitable for applications in construction, automotive and packaging industries (Ganesan et al., 2024). The use of banana fibres not only promotes sustainability but also reduces the dependency on synthetic fibres like glass or carbon, which are non-biodegradable and energy-intensive to produce.

Binders play a crucial role in composite materials by holding the reinforcement together and ensuring load transfer across the composite structure. The selection of an appropriate binder depends on mechanical performance requirements, processing conditions, and environmental considerations (Jiang et al., 2022). The two main types of binders used in composites include epoxy resins and polyester resins. The choice of binder type significantly impacts the overall performance of composite materials, influencing factors such as tensile strength, impact resistance, and environmental durability.

This research focuses on investigating the microstructural and mechanical properties of banana fibres-reinforced plastic composite, specifically analysing the effects of binder types. The study evaluates how varying proportions of waste PVC, PET, banana fibres, and different resin types (epoxy resin and polyester resin) influence mechanical properties, including tensile strength, compressive strength and flexural strength (Ahmad et al., 2024). Additionally, the research examines fibres-matrix interaction, porosity, and fracture behaviour using Scanning Electron Microscopy (SEM).

The findings will contribute to the advancement of innovative and sustainable composite materials, providing a pathway for eco-friendly alternatives to conventional composites in industrial applications. For instance according to (THEMAN, 2023), ceiling boards are majorly made of wood products which are posing danger to the environment by cutting down trees to produce. Plastic composites will provide an alternative to wood ceiling boards and hence reduce deforestation.

2. Methodology

2.1 Samples production

The composite samples were produced by mixing the matrix and fibre according to the volume fractions. Mass of each factor that fills the mould was measured in grams using analytical weighing balance and results recorded in Table 1: Masses in grams (g) of factors that fill moulds

Sample	PVC	PET	Epoxy	Polyester	Fibre
Compression	35.3972	20.623	33.5050	37.1450	5.5610
Flexural	15.6651	10.036	15.9964	18.0759	4.2278
tensile	7.01233	4.5803	12.4754	14.0972	2.2192

The sample production process began with the preparation of the raw materials, which included polyethylene terephthalate (PET), polyvinyl chloride (PVC), and banana fibres. PET and PVC were first ground into fine powders to improve their dispersion within the composite matrix. The banana fibres were prepared separately and used as reinforcement material. After preparation, the PET powder, PVC powder, and banana fibres were combined with either epoxy or polyester resin to form the composite. The binder played an important role in ensuring proper adhesion between the matrix and the reinforcing fibres. Figure 1: Summary of composite production process shows the summary of production of the composite.

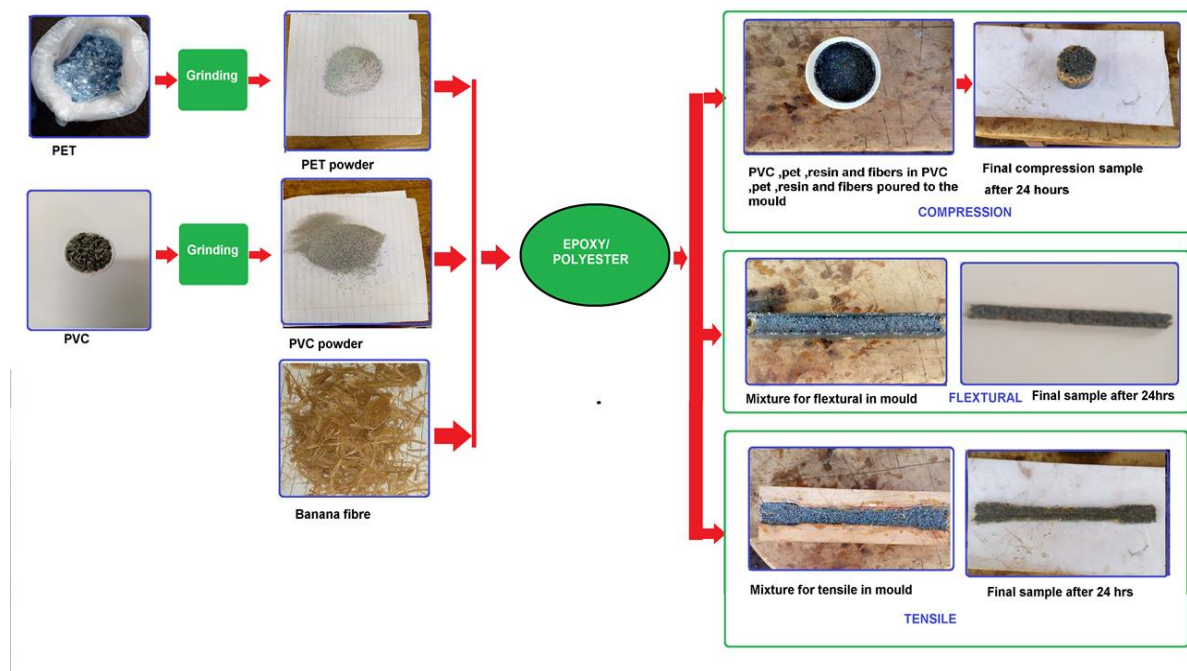


Figure 1.

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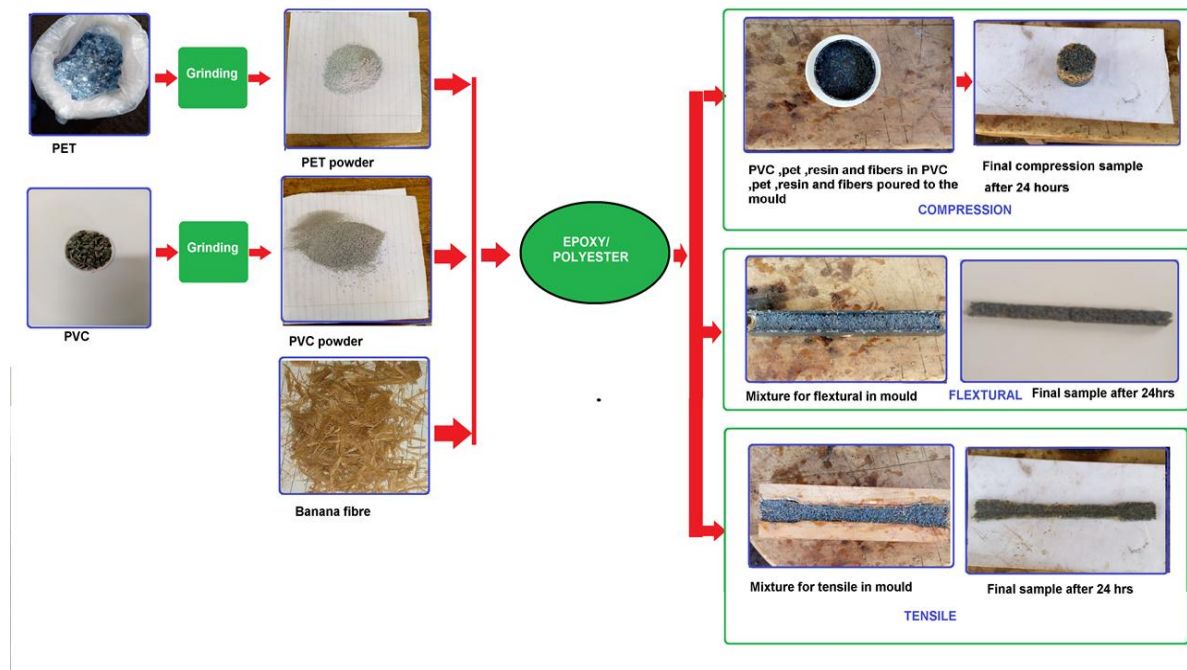


Figure 1: Summary of composite production process

The prepared composite mixture was then poured into different moulds depending on the intended mechanical test. After casting, the samples were left to cure for 24 hours to allow the resin to harden and achieve sufficient bonding among the composite constituents. The final cured samples were then ready for mechanical testing to evaluate their compression, flexural, and tensile properties.

2.2 Mould preparation

Three different moulds were used to make the samples as shown in Figure 2: Tensile test-piece (Source: (Yoon et al., 2019)), Figure 3: Tensile test samples and Figure 4: Compression test-piece (Source: (Sivalingam et al., 2025)). The three specimens were fabricated following the ASTM standards of each test. A MR8 real releasing agent was used to facilitate easy removal of composite from the mould after curing. Each composite was cured under a load of 1N for 24 hours before removing the mould.

2.3 Tensile test specimen preparation

The tensile test specimens were produced using a dog-bone shaped wooden mould designed to directly form specimens suitable for tensile testing according to ASTM D638. The dog-bone geometry shown in Figure 2: Tensile test-piece (Source: (Yoon et al., 2019)) ensures uniform stress distribution within the gauge length and reduces stress concentration near the gripping ends during testing (Jamalimehr et al., 2016).

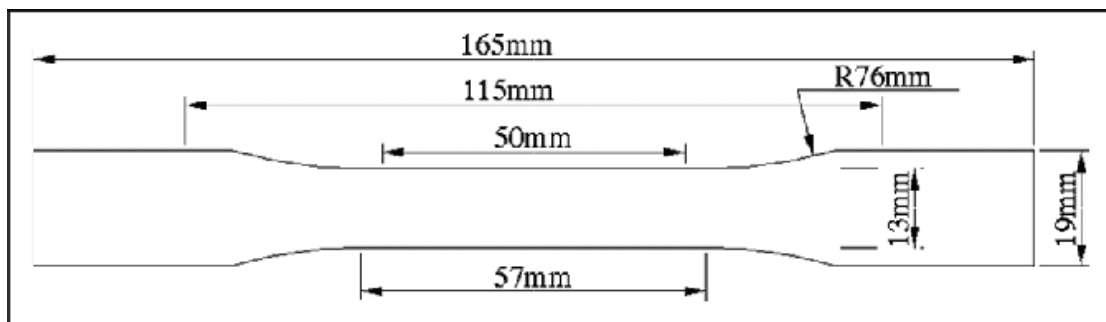


Figure 2: Tensile test-piece (Source: (Yoon et al., 2019))

Prior to fabrication, the mould surfaces were thoroughly cleaned using clean water and detergents to remove dust, debris, and any residual materials. Then the mould was dried using a piece of clean dry cloth. A uniform layer of MR8 real release agent was then applied to the mould cavity to prevent adhesion between the composite and the mould surface, thereby allowing easy removal of the specimens after curing.

A wooden mould was selected for specimen fabrication due to its cost-effectiveness, ease of machining, and availability, making it suitable for laboratory-scale composite production (THEMAN, 2023). Additionally, wood provides adequate dimensional stability for hand lay-up processes and allows easy customization of the dog-bone geometry. To compensate for its porous nature and to achieve a smooth specimen surface finish, the mould was properly sealed and coated with a release agent prior to use.

The hand lay-up technique was employed in the fabrication process. The required quantities of PVC, PET, and epoxy resin were measured according to the proportions specified in Table 2: Tensile test mix ratios for epoxy resin. The resin system was prepared by thoroughly mixing the epoxy resin in a clean container to achieve a homogeneous consistency. Stirring was carried out slowly and carefully to minimize air entrapment and to ensure proper blending of the matrix constituents.

Table 2: Tensile test mix ratios for epoxy resin

PVC (vol%)	PET (vol%)	Epoxy Resin (vol%)	Fibre (vol%)	Sample
25 (1.7531g)	25 (1.1451g)	28 (3.4931g)	20 (0.4438g)	T-1
20 (1.4025g)	20(0.9161g)	28 (3.4931g)	30 (0.6658g)	T-2
15 (1.0519g)	15 (0.6871g)	28 (3.4931g)	40 (0.8877g)	T-3

The fibres were aligned in a unidirectional orientation (0°) along the longitudinal axis of the specimen, corresponding to the direction of tensile loading for reinforcement. A thin layer of the prepared resin mixture was first applied onto the mould surface. Subsequently, the fibres were then carefully placed along the length of the mould cavity and gently pressed to ensure proper alignment. Additional resin was applied using a brush to ensure complete wetting of the fibres and the process was repeated until the required thickness was achieved. Care was taken throughout the lay-up process to maintain proper fibre alignment and uniform resin distribution, as these are critical factors influencing tensile strength.

To improve consolidation and eliminate trapped air, gentle rolling and light manual pressure were applied during lay-up. The mould was also lightly tapped to facilitate the escape of entrapped air bubbles and to enhance compaction of the composite material.

The specimens were left to cure at ambient room temperature for 24 hours to allow complete polymerization of the epoxy matrix. After curing, the tensile specimens were carefully removed from the wooden mould. Minor finishing operations, including trimming and light polishing, were carried out to remove surface irregularities and to ensure smooth, uniform specimen geometry, which is essential for accurate tensile testing (ElKhoury & Berg, 2022a).

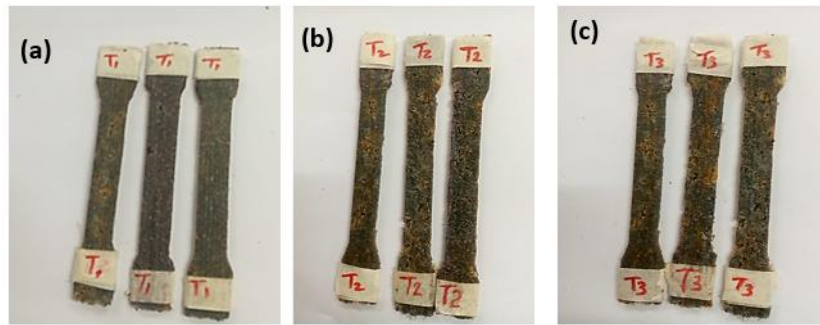


Figure 3: Tensile test samples

Three different specimen categories were produced by varying the matrix and fibre volume fractions as presented in Table 3: Tensile test mix ratios using polyester resin. The samples were labelled T1, T2, and T3 according to the mix ratios as shown in Figure 3: Tensile test samples. For each category, three replicate specimens were fabricated and labelled accordingly to ensure reliability and reproducibility of the experimental results.

Table 3: Tensile test mix ratios using polyester resin

PVC (vol%)	PET (vol%)	Polyester Resin (vol%)	Fibre (vol%)	Sample
25 (1.7531 g)	25 (1.1451 g)	28 (3.9472 g)	20 (0.4438 g)	BT-1
20 (1.4025 g)	20 (0.9161 g)	28 (3.9472 g)	30 (0.6658 g)	BT-2
15 (1.0518 g)	15 (0.6870 g)	28 (3.9472 g)	40 (0.8877 g)	BT-3

In addition, another set of specimens was fabricated using polyester resin as the matrix material while maintaining the same fibre orientation and fabrication procedure as described above. The tensile test specimens were produced using the same dog-bone shaped wooden mould and replicated three times per mix ratio. This enabled evaluation of the effect of matrix type on the tensile properties of the developed composite materials.

2.4 Compression test specimen

The compression test specimens were fabricated using a rigid metallic mould as summarised in Figure 4: Compression test-piece (Source: (Sivalingam et al., 2025)).

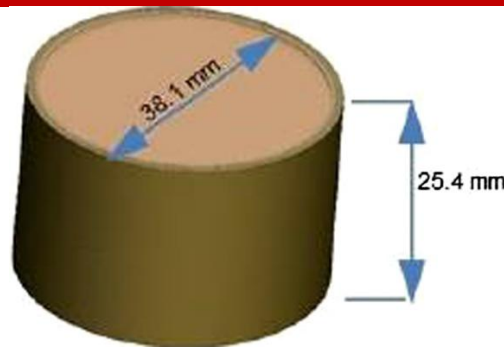


Figure 4: Compression test-piece (Source: (Sivalingam et al., 2025))

The mould cavity was thoroughly cleaned using clean water and detergents to remove dust and residual materials, after which a thin layer of MR8 release agent was applied to all internal surfaces to prevent adhesion of the composite and to facilitate easy demoulding after curing. The measured proportions shown in Table 4: Compression test mix ratio using epoxy resin, of matrix and fibre was mixed in beaker and poured into the mould.

Table 4: Compression test mix ratio using epoxy resin

PVC (vol%)	PET (vol%)	EPOXY RESIN (vol%)	Fibre (vol%)	Sample
25 (8.8493 g)	25 (5.1558)	28 (9.3814 g)	20 (1.1122 g)	C-1
20 (7.0794 g)	20 (4.1247g)	28 (9.3814 g)	30 (1.6683 g)	C-2
15 (5.3096 g)	15 (3.0935g)	28 (9.3814 g)	40 (2.2244 g)	C-3

The measured masses of PVC, PET and epoxy resin were put into a beaker, then stirred to obtain a homogeneous matrix. Stirring was done out slowly to ensure uniform dispersion and minimizing void formation. The fibres were randomly added into the matrix and continuously stirred to achieve even fibre distribution throughout the mixture. Once a uniform mixture was obtained, the composite slurry was carefully poured into the prepared mould cavity. Gentle tapping and slight vibration of the mould were applied to release trapped air bubbles and promote proper compaction of the mixture (Sam-Daliri et al., 2023).



Figure 5: Compression test specimens

The filled mould was left to cure at room temperature for 24 hours for curing of the epoxy system. When the composite was cured, the samples were demoulded. The surfaces were lightly polished to achieve smooth and parallel faces, ensuring accurate load distribution during compression testing. Three different specimens were produced by varying the volume fractions of matrix and fibre as summarised in Table 5: Compression test mix ratios using polyester resin

PVC (vol%)	PET (vol%)	POLYESTER RESIN (vol%)	Fibre (vol%)	Sample
25 (8.8493 g)	25 (5.1558 g)	28 (10.4104 g)	20 (1.1122 g)	BC-1
20 (7.0794 g)	20 (4.124 7g)	28 (10.4104 g)	30 (1.6683 g)	BC-2
15 (5.3096 g)	15 (3.0935 g)	28 (10.4104 g)	40 (2.2244 g)	BC-3

. To improve experimental reliability and reproducibility, three replicate specimens were fabricated for each experimental run and labelled as C1, C2 and C3 as shown in **Error! Not a valid bookmark self-reference..** These variations enabled the investigation of the influence of fibre content and matrix composition on the compressive properties of the composite materials.

Table 5: Compression test mix ratios using polyester resin

PVC (vol%)	PET (vol%)	POLYESTER RESIN (vol%)	Fibre (vol%)	Sample
25 (8.8493 g)	25 (5.1558 g)	28 (10.4104 g)	20 (1.1122 g)	BC-1
20 (7.0794 g)	20 (4.124 7g)	28 (10.4104 g)	30 (1.6683 g)	BC-2
15 (5.3096 g)	15 (3.0935 g)	28 (10.4104 g)	40 (2.2244 g)	BC-3

Another three samples were produced using polyester resin as the matrix. The samples were labelled **CB1**, **CB2** and **CB3** respectively. In each of the sample type three replications were produced to ensure reliability and accuracy of the test model. These variations enabled the

investigation of the influence of matrix type and composition on the compressive properties of the composite materials.

2.5 Flexural test specimen preparation

The flexural test specimens were produced using a flat, rigid metallic mould designed to achieve the required rectangular dimensions for three-point bending tests as shown in Figure 6: Bending test piece (Source: (Ganesan et al., 2024))

The hand lay-up technique was employed in the fabrication process. The required quantities of PVC, PET, and epoxy resin were first measured according to the proportions specified in Table 6: Flexural test mix ratios using epoxy resin

PVC (vol%)	PET (vol%)	EPOXY RESIN (vol%)	Fibre (vol%)	Sample
25 (3.9163g)	25 (2.5089g)	28 (4.4790g)	20 (0.8456g)	F-1
20 (3.1330g)	20 (2.0071g)	28 (4.4790g)	30 (1.2683g)	F-2
15 (2.3498g)	15 (1.50534g)	28 (4.4790g)	40 (1.6911g)	F-3

For reinforcement, the fibres were arranged in a unidirectional orientation at 0° relative to the longitudinal axis of the specimen. A thin layer of the prepared resin mixture was first applied onto the mould surface. The first layer of fibres was then carefully placed along the 0° direction and gently pressed to ensure proper alignment. Additional resin was applied over the fibre layer using a brush to achieve complete wetting. This process was repeated layer by layer until the desired thickness was attained. Care was taken throughout the lay-up process to maintain fibre alignment and uniform resin distribution.

To enhance consolidation and remove trapped air, gentle rolling and light manual pressure were applied over each layer during lay-up. Slight tapping of the mould was also performed to facilitate the escape of entrapped air bubbles and to improve compaction of the laminate. The laminate was left to cure at ambient room temperature for 24 hours to allow complete polymerization of the epoxy system. After curing, the composite plate was carefully removed from the mould. The edges were lightly polished to obtain smooth, straight, and parallel surfaces, ensuring accurate stress distribution during flexural testing. The samples were labelled as shown in Figure 7: Flexural test specimens

Three different specimen categories were produced by varying the matrix and fibre volume fractions as presented in Table 7: Volume mix for flexural test specimens using polyester resin

PVC (vol%)	PET (vol%)	Polyester Resin (vol%)	Fibre (vol%)	Sample
25 (3.9163g)	25 (2.5089g)	28 (5.0361g)	20 (0.8456g)	BF-1
20 (3.1330g)	20 (2.0071g)	28 (5.06361g)	30 (1.2683g)	BF-2
15 (2.3498g)	15 (1.5053g)	28 (5.06361g)	40 (1.6911g)	BF-3

In addition, another set of specimens was fabricated using polyester resin as the matrix material while maintaining the same 0° fibre orientation and hand lay-up procedure. These specimens were similarly replicated three times per category to enhance the statistical reliability of the flexural test results. The variations in matrix type and composition enabled evaluation of their influence on the flexural properties of the developed composite materials.. For each category, three replicate specimens were fabricated and labelled accordingly to ensure reliability and reproducibility of the experimental results.

Table 7.

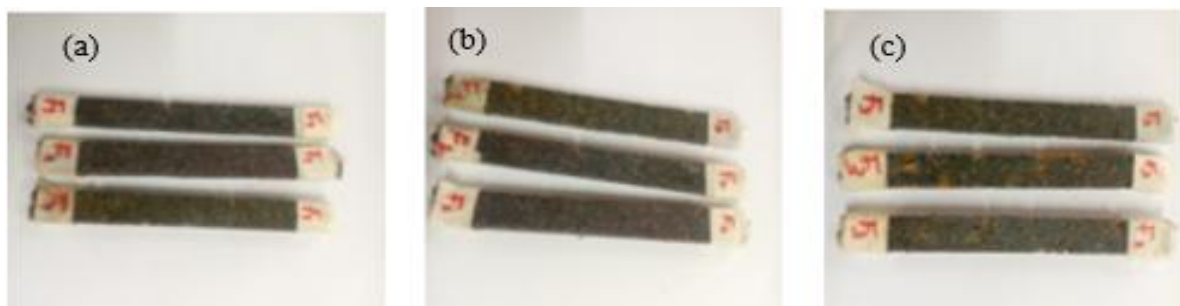


Figure 7. The resin system was prepared by mixing the epoxy resin thoroughly in a clean beaker to achieve uniform consistency. Stirring was carried out slowly and carefully to minimize air entrapment and to ensure proper blending of the matrix constituents.

Table 6: . Prior to fabrication, the mould surfaces were thoroughly cleaned using clean water and detergents to eliminate dust, grease, and any residual composite material (Kallel & Elleuch, 2025). A uniform layer of polyvinyl alcohol release agent was then applied to the mould cavity to prevent bonding between the laminate and the mould surface, thereby ensuring easy demoulding after curing.

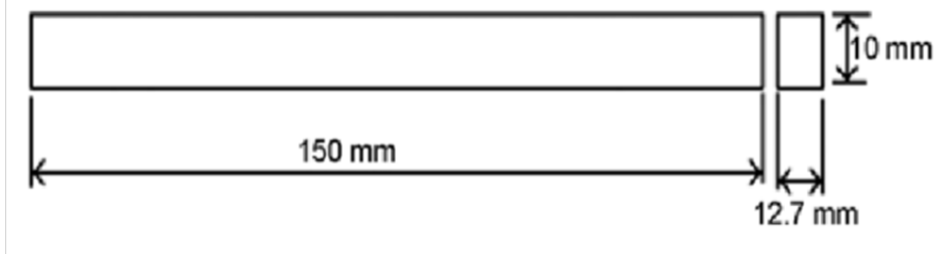


Figure 6: Bending test piece (Source: (Ganesan et al., 2024))

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For reinforcement, the fibres were arranged in a unidirectional orientation at 0° relative to the longitudinal axis of the specimen. A thin layer of the prepared resin mixture was first applied onto the mould surface. The first layer of fibres was then carefully placed along the 0° direction and gently pressed to ensure proper alignment. Additional resin was applied over the fibre layer using a brush to achieve complete wetting. This process was repeated layer by layer until the desired thickness was attained. Care was taken throughout the lay-up process to maintain fibre alignment and uniform resin distribution.

To enhance consolidation and remove trapped air, gentle rolling and light manual pressure were applied over each layer during lay-up. Slight tapping of the mould was also performed to facilitate the escape of entrapped air bubbles and to improve compaction of the laminate. The laminate was left to cure at ambient room temperature for 24 hours to allow complete polymerization of the epoxy system. After curing, the composite plate was carefully removed from the mould. The edges were lightly polished to obtain smooth, straight, and parallel surfaces, ensuring accurate stress distribution during flexural testing. The samples were labelled as shown in Figure 7: Flexural test specimens

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15 (2.3498g)	15 (1.5053g)	28 (5.06361g)	40 (1.6911g)	BF-3

In addition, another set of specimens was fabricated using polyester resin as the matrix material while maintaining the same 0° fibre orientation and hand lay-up procedure. These specimens were similarly replicated three times per category to enhance the statistical reliability of the flexural test results. The variations in matrix type and composition enabled evaluation of their influence on the flexural properties of the developed composite materials.. For each category, three replicate specimens were fabricated and labelled accordingly to ensure reliability and reproducibility of the experimental results.

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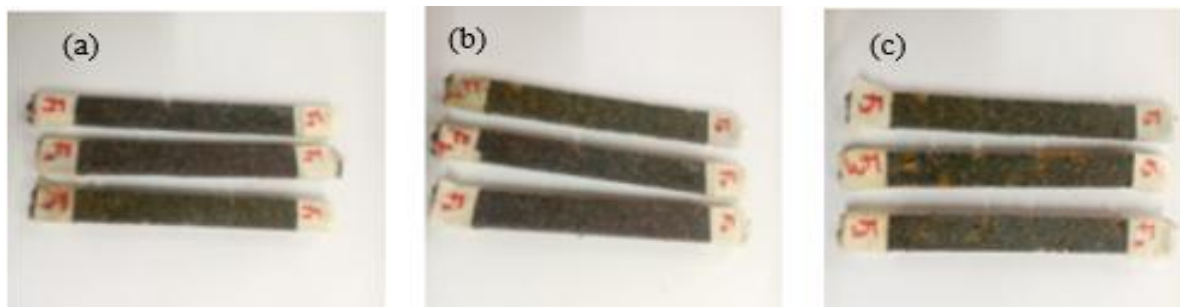


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flexural test results. The variations in matrix type and composition enabled evaluation of their influence on the flexural properties of the developed composite materials.

2.6 Microstructural Examination

Microstructural analysis was conducted to examine the surface morphology and interfacial characteristics of the banana fibre–reinforced epoxy/PET/PVC composite using a JEOL JCM-7000 NeoScope Scanning Electron Microscopy (SEM) shown in Figure 8: Scanning electron microscope. Fractured specimens obtained after mechanical testing were selected to ensure that the microstructural features observed represented actual failure mechanisms within the composite. The samples were first cut into appropriate sizes to fit the specimen chamber of the microscope. Loose debris and dust particles were carefully removed from the fracture surfaces using compressed air to prevent imaging artefacts. The specimens were then oven-dried at temperature of 60°C to eliminate moisture, particularly due to the hydrophilic nature of banana fibres, which could otherwise affect imaging quality under vacuum conditions (Venkataravanappa et al., 2023).



Figure 8: Scanning electron microscope

Since polymer-based composites are generally non-conductive, the prepared samples were mounted on aluminium stubs using conductive carbon adhesive tape to ensure proper grounding. To prevent surface charging during imaging, each specimen was sputter-coated

with a thin layer of gold to enhance electrical conductivity. The coating thickness was kept minimal to preserve surface details while improving signal quality.

The microstructural examination was carried out using a Scanning Electron Microscope operated in high vacuum mode with pressure of 10⁻⁵ Pa. Secondary electron imaging was employed to obtain detailed information on surface topography and fracture features. An accelerating voltage of 15 kV was selected to provide adequate penetration and contrast between the banana fibres, epoxy matrix, and thermoplastic phases (PET and PVC). A working distance of approximately 15–16 mm was maintained to achieve a suitable depth of field and image clarity. Micrographs were captured at a magnification of X30 to evaluate fibre distribution, dispersion of thermoplastic phases, interfacial bonding, void content, and evidence of fibre pull-out.

The obtained SEM images were subsequently analysed qualitatively to assess fibre–matrix adhesion, phase dispersion, fracture behaviour, and the presence of defects such as voids. These morphological observations were correlated with the mechanical performance of the composite to explain variations in compressive strength and failure mechanisms.

3. Results and Discussion

3.1 Mechanical performance

The results presented in Table 8-10 show the mechanical performance of the developed composites under tensile, compressive and flexural loading conditions. In this study, samples T, C and F represent composites prepared using epoxy resin, while BT, BC and BF represent composites prepared using polyester resin. The comparison therefore illustrates the influence of resin type on the mechanical behaviour of the banana fibre reinforced plastic composites.

3.1.1 Tensile Properties for epoxy and polyester binders

The tensile results indicate a noticeable difference between epoxy-based samples (T1, T2 and T3) and polyester-based samples (BT1, BT2 and BT3). The polyester samples exhibit slightly higher yield strength and ultimate tensile strength compared to the epoxy samples as shown in Table 8. For instance, the yield strength of polyester samples ranges between 31.87–33.72 MPa, while the epoxy samples range between 29.55–31.40 MPa. Similarly, the ultimate tensile strength for polyester samples reaches 37.69 MPa, whereas the maximum value for epoxy samples is 33.07 MPa.

Table 8: tensile test results

Sample	Yield (MPa)	UTS (MPa)	E (GPa)	Elongation (mm)
BT1	33.72	35.00	2.26	0.18
BT2	32.78	36.32	2.34	0.18
BT3	31.87	37.69	2.42	0.17
T1	31.40	30.38	2.47	0.16
T2	30.46	31.70	2.55	0.16
T3	29.55	33.07	2.63	0.16

This behaviour suggests that polyester resin provided relatively better stress transfer between the matrix and the banana fibre reinforcement. However, the Young's modulus of the epoxy samples (2.47–2.63 GPa) is slightly higher than that of the polyester samples (2.26–2.42 GPa), indicating that epoxy composites exhibited greater stiffness. The observed improvement in stress transfer for polyester-based composites is attributed to enhanced fibre wetting and mechanical interlocking between the matrix and banana fibre reinforcement. Polyester resins typically exhibit lower viscosity, which facilitates better impregnation of natural fibres and reduces void content, thereby improving interfacial adhesion and load transfer efficiency. Similar observations have been reported by (Raut et al., 2024), who noted that adequate fibre dispersion and wetting in polyester matrices contribute significantly to improved mechanical performance in natural fibre composites. In contrast, the slightly higher Young's modulus observed in epoxy-based composites is consistent with the inherently superior stiffness of epoxy resins, which arises from their highly crosslinked molecular structure. This dense network restricts molecular mobility, resulting in greater resistance to elastic deformation. According to Jawaid and Abdul Khalil (2011), epoxy composites generally exhibit higher stiffness and modulus compared to polyester systems due to stronger interfacial bonding and superior matrix rigidity.

The elongation values show a gradual reduction in the epoxy samples compared to polyester, indicating that epoxy composites were relatively more brittle. Overall, polyester resin enhanced tensile strength, while epoxy improved stiffness of the composite. This behaviour is primarily attributed to the highly crosslinked molecular structure of epoxy resins, which restricts chain mobility and limits plastic deformation under tensile loading. As a result, epoxy composites tend to exhibit lower strain-to-failure despite their superior stiffness. Similar

findings have been reported by (Gassan, 2002), who noted that natural fibre–epoxy composites typically show reduced elongation due to strong interfacial bonding and rigid matrix networks.

The tensile test results show that polyester-based composites exhibited higher tensile strength compared to epoxy-based composites. The mean ultimate tensile strength of polyester composites (BT samples) was 36.34 MPa, whereas epoxy composites (T samples) recorded a mean value of 31.72 MPa. This indicates that polyester resin enhanced the ability of the composite to withstand axial tensile loading. This behaviour can be attributed to improved fibre wetting and dispersion in the polyester matrix, which promotes effective stress transfer between the banana fibres and the matrix. Polyester resins typically have lower viscosity, allowing better impregnation of natural fibres and reducing the likelihood of void formation, which are known to act as stress concentrators. Similar observations have been reported by (Raut et al., 2024), who found that good fibre–matrix interaction in polyester-based natural fibre composites significantly improves tensile strength.

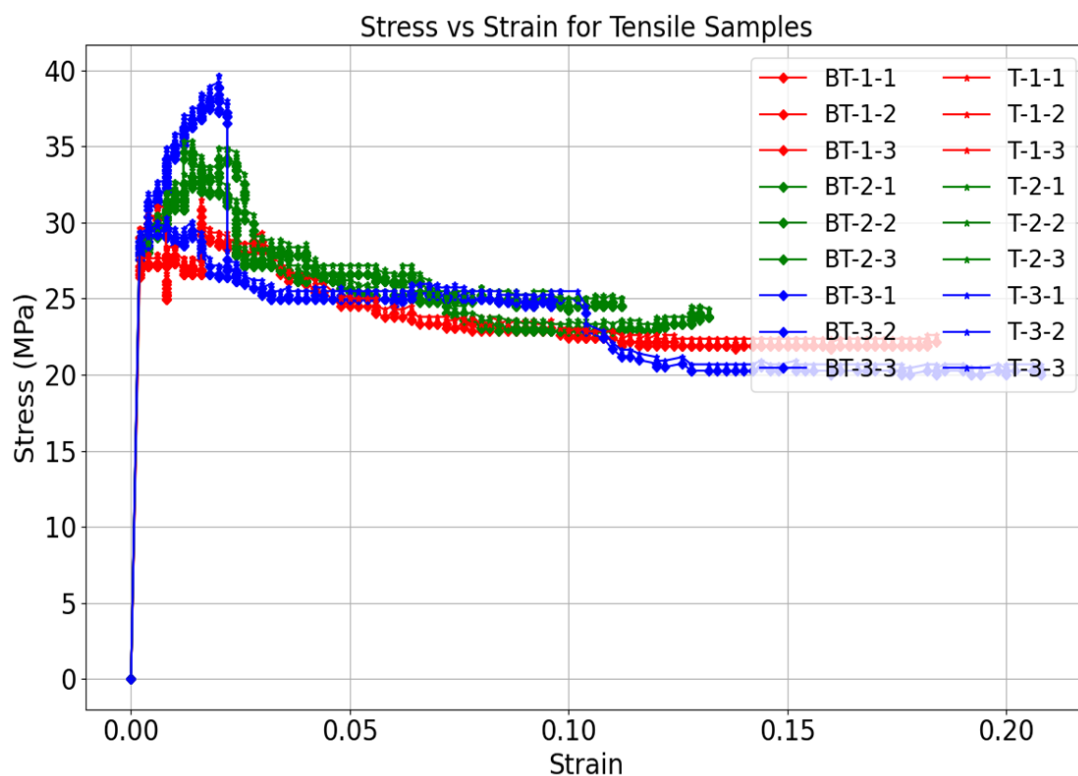


Figure 9: Tensile stress strain analysis

Analysis of the tensile properties revealed clear trends associated with material composition as shown in Figure 9. Samples comprising low PVC/PET content, and high fibre loading consistently exhibited the highest yield strength, ultimate tensile strength (UTS), and

elongation, as reflected in the blue curves. This behaviour is attributed to the increased load-bearing contribution of the banana fibres and improved stress transfer at higher fibre volume fractions, which has been widely reported in natural fibre composites (Raut et al., 2024). Similarly, samples with low PVC/PET content, polyester resin, and moderate fibre content recorded the second highest yield strength and UTS values, again demonstrating better characteristics over epoxy resin samples of the same mixture ratios, though this group recorded the lowest elongation at break, as shown in the green curves. Samples containing moderate PVC/PET content, epoxy resin, and low fibre loading exhibited the lowest yield strength and UTS, with epoxy-based formulations in this category performing marginally better than their polyester resin equivalents at the same mixture ratios. However, this group recorded the second highest elongation at break, suggesting a degree of retained ductility despite the reduced reinforcement content, as indicated by the red curves. This behaviour aligns with findings by (Mohammed et al., 2023), who noted that reduced fibre content in polymer composites allows greater matrix-dominated deformation, thereby increasing elongation. These findings collectively indicate that increasing fibre content in conjunction with polyester resin proportions and reduced PVC/PET loading is generally associated with enhanced tensile strength, while moderate reinforcement levels with epoxy resin tend to favour greater flexibility over stiffness.

The improved tensile performance of polyester composites is attributed to better stress transfer between the matrix and banana fibre reinforcement, which enhances the load-bearing capability of the fibres. This can be linked to the lower viscosity of polyester resin, which promotes better fibre wetting and dispersion, leading to improved interfacial bonding and reduced void content. Similar findings have been reported by (Raut et al., 2024), who observed that enhanced fibre–matrix interaction in polyester-based natural fibre composites significantly improves tensile strength. However, epoxy composites demonstrated slightly higher stiffness, as indicated by their modulus values in the results Table 1: Masses in grams (g) of factors that fill moulds

Sample	PVC	PET	Epoxy	Polyester	Fibre
Compression	35.3972	20.623	33.5050	37.1450	5.5610
Flexural	15.6651	10.036	15.9964	18.0759	4.2278
tensile	7.01233	4.5803	12.4754	14.0972	2.2192

The sample production process began with the preparation of the raw materials, which included polyethylene terephthalate (PET), polyvinyl chloride (PVC), and banana fibres. PET and PVC were first ground into fine powders to improve their dispersion within the composite matrix. The banana fibres were prepared separately and used as reinforcement material. After preparation, the PET powder, PVC powder, and banana fibres were combined with either epoxy or polyester resin to form the composite. The binder played an important role in ensuring proper adhesion between the matrix and the reinforcing fibres. Figure 1: Summary of composite production process shows the summary of production of the composite.

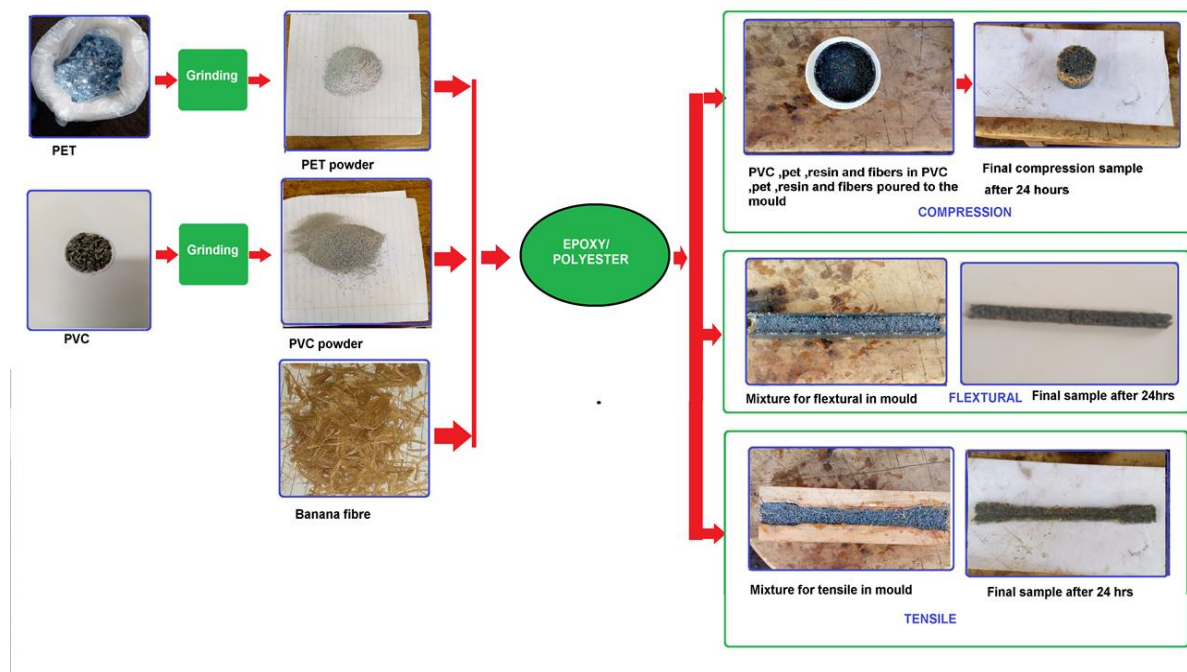


Figure 1. This suggests that epoxy resin contributed to a more rigid composite structure, although with slightly reduced tensile strength.

3.1.2 Compressive Properties for epoxy and polyester binders

The compressive test results reveal a similar trend. Polyester-based samples (BC1, BC2 and BC3) recorded higher compressive strength compared to epoxy-based samples (C1, C2 and C3). The ultimate compressive strength (UCS) for polyester composites ranges from 26.05–31.07 MPa, whereas epoxy composites range from 21.43–26.45 MPa as shown in Table 9.

Table 9: Compressive test results

Sample	Yield (MPa)	UCS (MPa)	E (GPa)	Shortening (mm)
--------	-------------	-----------	---------	-----------------

BC1	4.34	26.05	0.36	0.16
BC2	8.14	28.43	0.12	0.17
BC3	12.25	31.07	0.64	0.17
C1	2.02	21.43	0.15	0.15
C2	5.82	23.81	0.32	0.16
C3	9.94	26.45	0.85	0.16

At low fibre content (C-1 and BC1), the high matrix composition provides better structural continuity and resistance to crushing. The abundant PVC, PET and resin phases effectively absorb compressive stress and prevent micro-instability of fibres. Similar observations have been reported by (Raut et al., 2024), who noted that matrix-dominated composites exhibit better resistance to compressive deformation due to the uniform stress distribution within the polymer phase

At moderate fibre content (C-2 and BC2), a balance is achieved between rigidity and load transfer. The fibres begin to contribute to compressive stiffness by restricting matrix deformation, while the matrix still sufficiently binds the structure. This condition is typically associated with optimum compressive performance. This combination is often associated with peak compressive performance, as also highlighted by (Sam-Daliri et al., 2023), who reported that an optimal fibre volume fraction maximizes mechanical properties by balancing reinforcement and matrix support.

At higher fibre content (C-3 and BC3), however, reduced matrix availability limits fibre encapsulation. This leads to, fibre micro-buckling, weak interfacial bonding and formation of void. As a result, excessive fibre reduces the composite's ability to withstand compressive loads effectively, making it more prone to premature failure. (Kheizrloo et al., 2021) similarly observed that high fibre content in natural fibre composites can reduce compressive strength due to poor stress transfer and increased structural discontinuities.

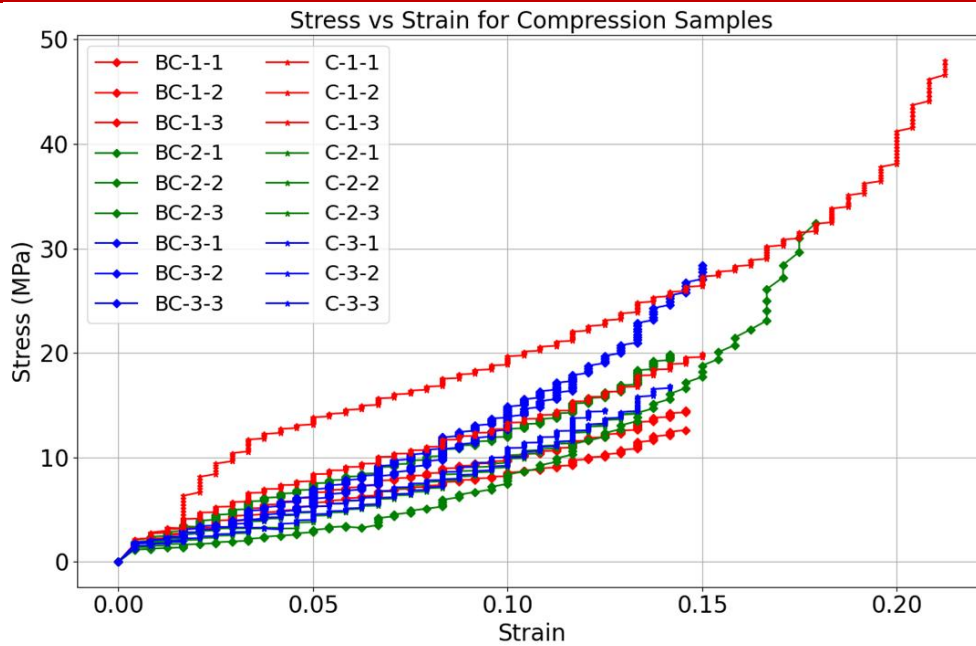


Figure 10: Stress strain curves for compressive test results

The compressive strength results revealed compositional trends that were shown in Figure 10. Samples comprising moderate PVC/PET content, epoxy resin, and low fibre loading demonstrated higher compressive strength compared to their polyester resin of equivalent mixture ratios, as represented by the red curves. Similar observations have been reported by (Mohammed et al., 2023), who noted that epoxy matrices tend to perform better under compressive loading due to their rigidity and strong intermolecular bonding. Samples with low PVC/PET content, polyester resin, and high fibre loading exhibited higher compressive strength relative to epoxy resin samples of the same mixture ratios, as shown in the blue curves. This suggests that polyester-based systems enhance mechanical performance under fibre-dominated conditions, likely due to improved fibre wetting and interfacial bonding, which facilitate effective load transfer and delay fibre micro-buckling. (Raut et al., 2024) similarly reported that good fibre–matrix interaction in polyester composites contributes to improved mechanical performance, particularly at higher fibre contents. Polyester-based systems enhances mechanical performance under compressive loading conditions. Samples with low PVC/PET content, polyester resin, and moderate fibre loading displayed moderate compressive strength to their epoxy resin equivalents of the same mixture ratios, as indicated by the green curves. This imply that at intermediate fibre contents, the choice of resin system has a downward trend on compressive performance. These results suggest that fibre content and resin type interact differently under compressive loading.

The higher compressive strength in polyester composites is attributed to improved matrix continuity and stronger interfacial bonding, which helps prevent fibre micro-buckling under compressive loading. As the sample number increases from 1 to 3, both resin systems show a progressive increase in compressive strength and yield stress, indicating improved load-bearing capability of the composite structure. This implies that at intermediate fibre contents, the influence of resin type becomes less pronounced, and the composite behaviour reflects a balance between matrix stiffness and fibre reinforcement. (Ding et al., 2022) also highlighted that composite performance at intermediate fibre fractions depends on the interaction between fibre distribution, interfacial bonding, and matrix properties. However, the modulus values fluctuate across the samples, suggesting variations in internal stress distribution and possible differences in fibre dispersion within the matrix.

3.1.3 Flexural Properties

For the flexural tests, polyester-based samples (BF1, BF2 and BF3) again demonstrate higher strength compared to epoxy samples (F1, F2 and F3) as shown in Table 10. The maximum flexural strength for polyester composites is 36.04 MPa, while epoxy composites reach a maximum of 31.42 MPa. Polyester resins generally exhibit lower viscosity, which promotes better impregnation of banana fibres and reduces void formation, thereby improving interfacial bonding and delaying crack initiation under flexural loading. Similar findings have been reported by (Raut et al., 2024), who observed that improved fibre wetting and dispersion in polyester-based natural fibre composites significantly enhance flexural strength.

Table 10: Flexural test results

Sample	Yield (MPa)	Strength (MPa)	E (GPa)	Deflection at Yield (m)
BF1	31.320	34.250	1.431	0.012
BF2	31.050	36.040	1.595	0.011
BF3	31.510	33.770	1.467	0.011
F1	29.000	29.630	1.637	0.001
F2	28.730	31.420	1.800	0.002
F3	29.190	29.150	1.673	0.002

Flexural test results also indicate that polyester composites achieved higher bending strength compared to epoxy composites. The polyester samples (BF series) recorded a mean flexural

strength of 34.69 MPa, whereas epoxy samples (F series) recorded an average value of 30.07 MPa.

Flexural loading involves both tensile and compressive stresses, and therefore effective fibre–matrix bonding plays a critical role. This behaviour is commonly associated with the lower viscosity of polyester resins, which promotes better fibre wetting and reduces void formation, thereby improving interfacial adhesion. Similar observations have been reported by (Gassan, 2002), who found that enhanced fibre dispersion and bonding in polyester-based natural fibre composites significantly improve flexural properties. The improved performance of polyester composites indicates that the polyester matrix provided better stress distribution during bending. Additionally, the deflection values of polyester samples are higher than those of epoxy samples, indicating better flexibility and energy absorption capacity. It combines both tensile and compressive stresses within the material. Therefore, effective fibre–matrix bonding is essential for resisting crack initiation and propagation during bending. The improved flexural strength observed in polyester composites suggests better stress distribution and improved load transfer between the reinforcement and matrix. According to (ElKhoury & Berg, 2022b), the flexural performance of natural fibre composites is strongly influenced by the balance between matrix rigidity and fibre–matrix adhesion, which can sometimes result in polyester outperforming epoxy in bending applications. Although epoxy composites exhibited slightly lower flexural strength, they maintained good structural rigidity, which is consistent with the higher modulus values observed in the experimental data.

3.1.4 Overall Mechanical Performance

The overall comparison of the mechanical properties indicates that polyester resin produced composites with higher strength in tensile, compressive and flexural loading conditions, while epoxy resin contributed to slightly higher stiffness of the composite structure. Polyester resins generally exhibit lower viscosity, which promotes better fibre wetting, improved dispersion, and reduced void content during composite fabrication. These factors enhance interfacial bonding and facilitate more efficient stress transfer from the matrix to the banana fibre reinforcement, resulting in improved strength across different loading modes. Similar findings have been reported by (Raut et al., 2024), who observed that enhanced fibre–matrix interaction in polyester-based natural fibre composites significantly improves tensile, compressive, and flexural performance. (ElKhoury & Berg, 2022a) reported that epoxy-based natural fibre

composites typically exhibit higher stiffness due to stronger intermolecular bonding and higher crosslink density, even though their strength response may vary depending on processing and fibre treatment conditions.

This behaviour can be attributed to differences in the mechanical characteristics and bonding mechanisms of the two matrix systems. Polyester resin appears to provide more effective load transfer and strength enhancement, whereas epoxy resin contributes to improved rigidity and structural stability.

3.2. Microstructural Examination

Scanning Electron Microscopy (SEM) analysis was conducted on the fractured surfaces of composite samples subjected to tensile, compressive, and flexural loading shown in Figure 11 to investigate the underlying failure mechanisms and correlate them with the observed mechanical performance. The composites were developed using two different matrixes; polyester resin- BT, BC, BF and epoxy resin-T, C, F samples. Post-failure SEM examination provides critical insight into microstructural features such as porosity and crack propagation paths which collectively govern the mechanical behaviour of composite materials.

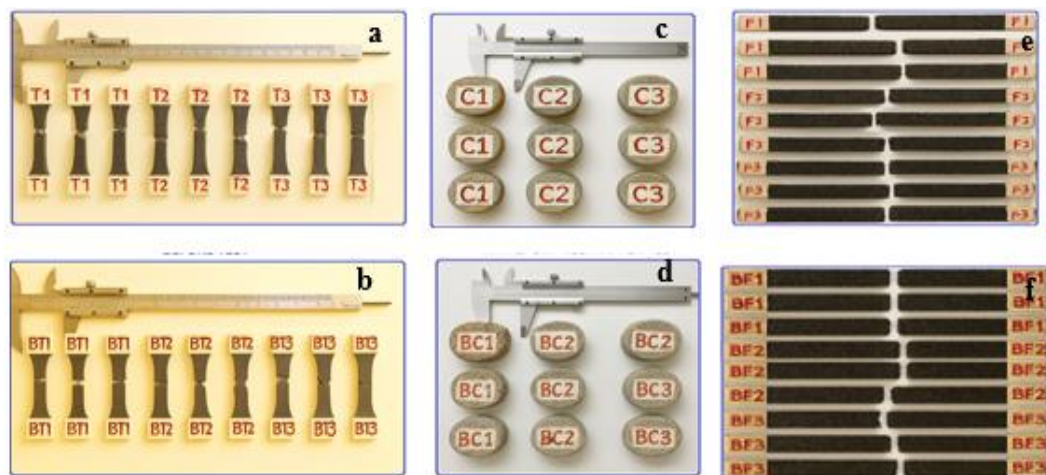


Figure 11: Samples after mechanical testing; (a, b) tensile test samples for epoxy and polyester resin binders respectively, (c, d) compression test samples for epoxy and polyester resin binders respectively, and (e, f) flexural test samples for epoxy and polyester resin binders respectively.

The analysis focuses on comparing how the two matrix systems influence the structural integrity of the composites under different loading conditions. A detailed microstructural analysis was conducted with emphasis on identifying defects such as voids, crack deflection, and matrix continuity, as these features are critical in governing and explaining the observed variations in tensile, compressive, and flexural strength during mechanical testing.

3.2.1 Microstructural analysis of the tensile specimens

The SEM micrographs of the tensile samples illustrate notable differences in fracture morphology between polyester-based composites (BT series) and epoxy-based composites (T series), largely influenced by matrix properties and interfacial bonding as shown of Figure 12.

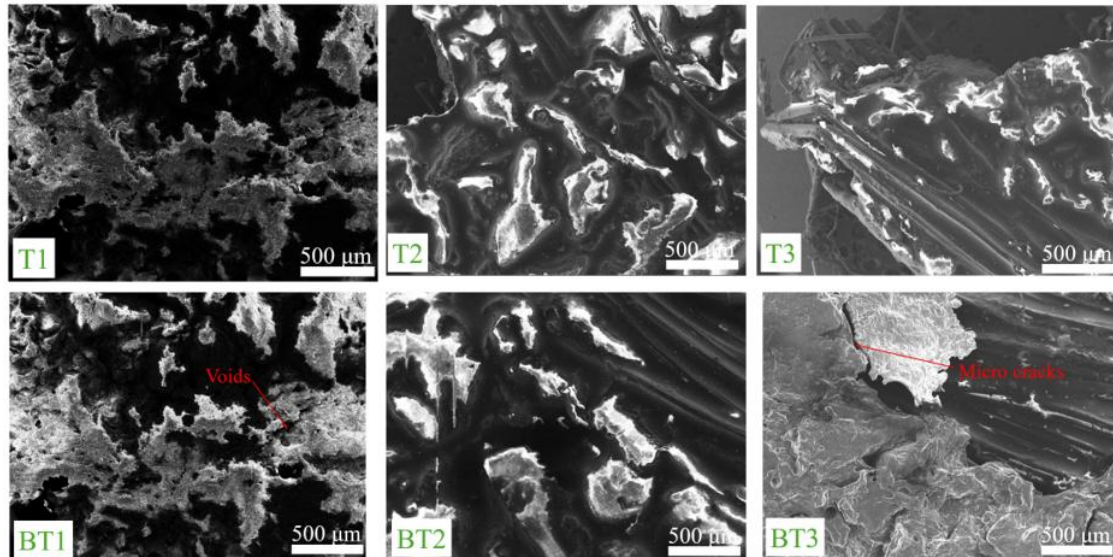


Figure 12: Tensile specimens under microscope

In the polyester composites (BT1–BT3), the fracture surfaces are generally characterized by higher porosity and weaker cohesion. BT1 exhibits a highly irregular and porous structure with fragmented particles and visible voids, indicating poor fibre wetting and weak interfacial adhesion. These defects act as stress concentrators, leading to early crack initiation and rapid propagation under tensile loading. As the composition improves in BT2 and BT3, the microstructure becomes denser, fewer microcracks and reduced voids. However, microcracks and localized fissures are still evident, suggesting that polyester resin limits complete stress transfer efficiency, resulting in predominantly brittle fracture behaviour.

Epoxy-based tensile samples (T1–T3) display a more uniform and cohesive microstructure with significantly improved fibre-matrix interaction. T1 shows some porosity but retains better structural continuity compared to BT1, reflecting improved adhesion characteristics of epoxy resin. With increasing reinforcement and resin content in T2 and T3, the fracture surfaces become denser and more integrated, with minimal voids and strong interfacial bonding. Features such as fibre bridging, crack deflection, and resistance to fibre pull-out are evident, indicating enhanced energy absorption during failure. These mechanisms contribute to delayed crack propagation and improved tensile strength. Overall, epoxy composites demonstrate good

tensile performance due to their lower porosity, stronger interfacial adhesion, and more efficient stress transfer compared to polyester-based composites.

3.2.2 Microstructural analysis for Compression Samples

The SEM micrographs of the compression samples reveal distinct differences in failure morphology between polyester-based composites (BC series) and epoxy-based composites (C series) as shown in Figure 13, primarily influenced by matrix type and composition.

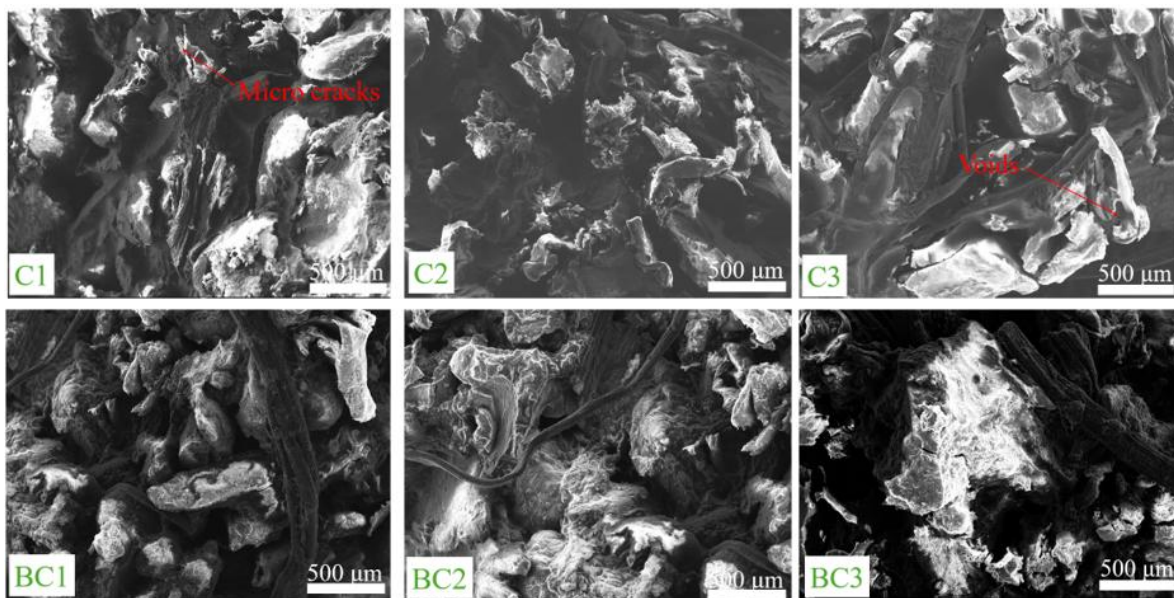


Figure 13: Microscopy image of compression test samples

Polyester composites (BC1–BC3), the microstructure generally exhibits higher levels of porosity and weaker interfacial bonding. Specifically, BC1 shows a loosely packed and fragmented structure with significant voids, indicating poor fibre dispersion and weak matrix cohesion. These features promote premature failure through pore collapse and localized crushing under compressive loading. As the composition improves toward BC2 and BC3, the structure becomes relatively denser with better fibre-matrix interaction; however, voids and microstructural discontinuities persist, suggesting that polyester resin still limits optimal stress transfer and structural integrity.

Epoxy-based compression samples (C1–C3) display a more compact and homogeneous microstructure with significantly reduced porosity. C1, although containing minor voids, shows better matrix continuity compared to BC1, indicating improved adhesion properties of epoxy resin. With increasing fibre and resin content in C2 and C3, the microstructure becomes

increasingly dense and well-integrated, with strong interfacial bonding between fibres and the matrix. The fracture surfaces reveal minimal debonding and instead show mechanisms such as fibre buckling and matrix deformation, which indicate efficient load transfer and enhanced resistance to compressive stresses. Overall, the epoxy composites demonstrate better structural integrity and reduced defect concentration compared to polyester composites.

These observations confirm that the matrix type plays a critical role in determining compressive failure behaviour. Polyester-based composites are more susceptible to void formation and interfacial weaknesses, leading to early failure, whereas epoxy-based composites exhibit improved cohesion, reduced porosity, and stronger fibre-matrix adhesion, resulting in enhanced compressive strength and durability.

3.2.3 Microstructural Analysis for Flexural Samples

The SEM micrographs shown in Figure 14 for the flexural samples reveal differences in structural integrity and failure mechanisms between polyester-based composites (BF series) and epoxy-based composites (F series) when subjected to bending loads.

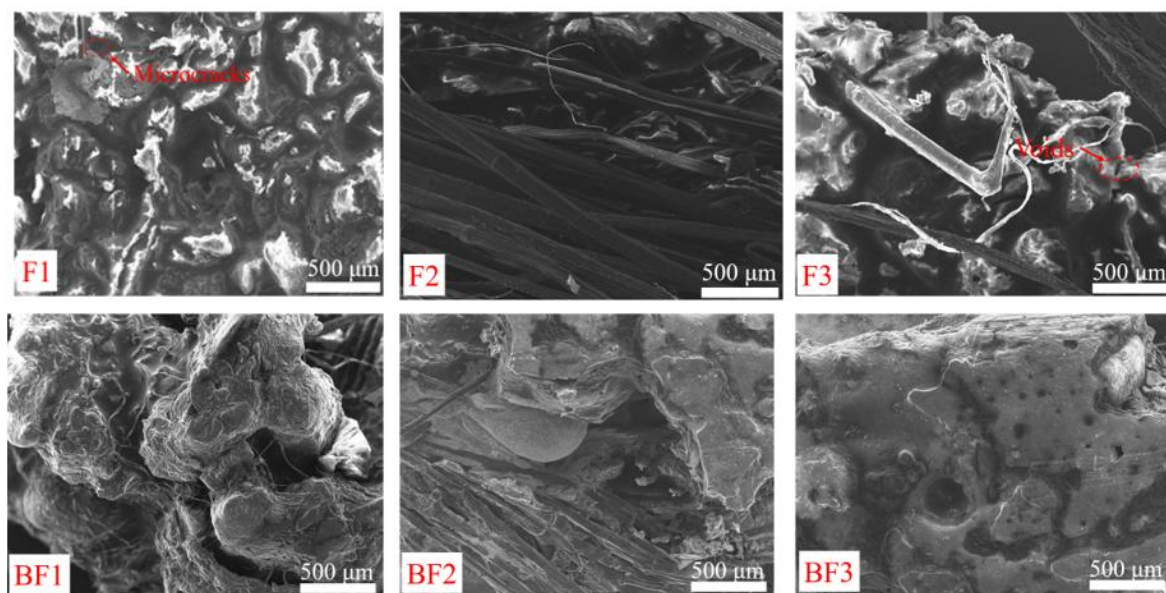


Figure 14: microscopy image of flexural test samples

Polyester composites (BF1–BF3), the microstructure typically shows a combination of fibrous regions and voids, indicating incomplete bonding and heterogeneous distribution of constituents. BF1 displays a relatively porous and irregular structure with weak fibre-matrix interaction, which promotes crack initiation on the tensile side during bending. In BF2 and

BF3, the structure becomes more organized, often exhibiting a layered morphology with improved fibre embedding and reduced fragmentation. Despite these improvements, the presence of voids and interfacial defects still limits effective stress transfer, resulting in moderate flexural performance.

Epoxy-based flexural samples (F1–F3) in figure 14 exhibit a more compact, homogeneous, and well-bonded microstructure. F1 shows improved cohesion compared to BF1, although minor porosity is still present. As the composition advances to F2 and F3, the microstructure becomes increasingly dense with strong fibre integration and minimal defects. The fracture surfaces reveal mechanisms such as fibre bridging, crack deflection, and strong resistance to fibre pull-out, all of which enhance the material's ability to withstand bending stresses. These features indicate efficient load transfer between the matrix and fibres and improved resistance to crack propagation. Consequently, epoxy-based composites demonstrate superior flexural strength and toughness compared to polyester-based composites, highlighting the importance of matrix selection in optimizing composite performance under flexural loading.

4. Conclusion

Polyester resin composites consistently outperform epoxy in yield strength, UTS, and elongation, especially when paired with low PVC/PET and high fibre content, confirmed superior binder–fibre synergy. Epoxy resin composites show slightly greater stiffness (1.56 GPa vs. 1.40 GPa), while polyester resin composites have higher yield strength (24.11 MPa), ultimate strength (33.18 MPa) and there was no major change observed for elongation. Flexural and tensile samples made with polyester resins demonstrated the best balance of strength and elongation due to the combined influence of binder type and fibre loading, promoting crack resistance and energy absorption across varied mix designs. Polyester resin composites exhibited superior microstructural characteristics compared to epoxy composites, showing improved fibre–matrix adhesion, more uniform dispersion, and fewer defects such as voids and fibre pull-out.

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Design of a Decentralized Automatic Generation Control Scheme Based on the Centroid Method for Effective Frequency and Tie-Line Power Regulation in Multi-Area Power Systems.

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Abstract

This paper proposes a novel decentralized Automatic Generation Control (AGC) scheme based on the centroid method to enhance frequency stability and tie-line power regulation in multi-area power systems. Addressing limitations of traditional centralized control architectures, the proposed approach leverages local measurements and minimal inter-area communication to estimate global system states accurately. The mathematical foundation of the centroid method is detailed, alongside the design of the decentralized control architecture, communication protocols, and parameter tuning strategies. Extensive simulations under various operating scenarios like load disturbances, generator outages, and communication delays demonstrate that the proposed scheme improves dynamic response, robustness, and scalability compared to conventional AGC methods. The results affirm the potential of centroid-based decentralized control for resilient and efficient power system operation.

Keywords: Decentralized AGC, Centroid Method, Frequency Regulation, Tie-Line Power Control, Multi-Area Power System, Distributed Control, Resilience

1. Introduction

The increasing integration of renewable energy sources, expanding interconnections, and dynamic load profiles have significantly elevated the complexity of modern power systems. To meet the increasing demand, additional power is to be extracted from the generators [1]. Power system is to generate and deliver power in an interconnected system as economically and reliably as possible while maintaining the voltage and frequency within permissible limit [2]. Maintaining system frequency and tie-line power flows within acceptable limits is crucial

for stability and efficiency. Traditional centralized AGC schemes, while effective, face challenges such as single points of failure, communication bottlenecks, and limited scalability.

This motivates the development of decentralized control strategies that rely on local measurements and limited communication, improving system resilience and scalability. However, decentralized methods often struggle with accurately estimating system-wide states, leading to suboptimal performance.

The centroid method offers a promising solution, providing a robust and communication-efficient means of estimating global variables by leveraging local data. This paper introduces a decentralized AGC scheme grounded in the centroid approach, aiming to enhance frequency and tie-line power regulation in multi-area systems.

The AGC system is temporally situated between Economic Dispatch (ED) and synchronous generator dynamics, and its primary role is to regulate frequency within and tie-line flows between control areas. Given appropriate choice of participation factors (feed-forward controller gains that govern the disaggregation of the area-level power requirement to individual generators), the AGC can be engineered to nudge system dynamics toward a steady-state operating point corresponding to economic optimality [3]. Load Frequency Control (LFC) with integral controller achieves zero steady state frequency error and fast dynamic response, but it exercises no control over the relative loadings of various generating stations of the control area [4].

2. Literature Review

AGC maintains system frequency and tie-line power flows via control actions based on Area Control Error (ACE) signals. Traditional centralized schemes utilize PI or PID controllers but are susceptible to single points of failure and scalability issues. Decentralized schemes include PI/PID decentralization, consensus algorithms, multi-agent systems, and model predictive control. While these methods improve robustness, they often require extensive communication or complex computations. The centroid method estimates the average of distributed measurements with minimal communication, showing robustness to noise and communication failures.

A. Related Studies.

Various studies have explored intelligent controllers to enhance power system performance beyond traditional PID controllers. For example, [5] found ANFIS outperforms fuzzy and PID controllers in reducing overshoot and settling time. Similarly, [6] concluded ANFIS provides better transient response in a four-area interlinked system with generation constraints. [7] used genetic algorithms to optimize fuzzy controllers, effectively mitigating load disturbances. [8] applied GRSA to optimize PI and PID controllers, surpassing other algorithms like C-PSO. [9] combined BFO and PS to optimize fuzzy PID controllers, demonstrating robustness under system variations. [10] utilized ANFIS trained via genetic algorithms for adaptive load frequency control in deregulated environments.

[11] compared ANN and fuzzy controllers, both outperforming conventional PID in hydrothermal systems. [12] tuned fractional order PID controllers with EV loads, improving dynamic responses. [13] enhanced ACE models for wind disturbances, comparing fuzzy PI and Fuzzy-GrHDP methods, both damping frequency oscillations effectively. [14] showed fuzzy controllers outperform PI in thermal systems under various loads. [15] implemented fuzzy AGC in Eskom's control center, achieving over 50% performance improvement. [16] found ANN and fuzzy controllers significantly better than traditional methods in hydrothermal systems. [17] designed neural network-based controllers with promising control accuracy.

[18] demonstrated HFNN controllers outperform PI/PID in response speed and stability. [19] used neural networks for multi-area load control, surpassing conventional controllers. [20] employed hybrid neural-fuzzy systems for AGC, enhancing stability against disturbances. [21] proposed neural fuzzy controllers managing load variability, reducing unnecessary control actions. [22] optimized PI controllers with RIME for hybrid systems, outperforming other algorithms. [23] introduced deep reinforcement learning for generator coordination, improving adaptability and control.

[24] integrated virtual synchronous renewables into AGC, increasing RES participation and system resilience. [25] modified CRP algorithms for economic dispatch, improving convergence speed and solution quality. [26] used transfer learning with deep neural networks for fast Pareto optimal dispatch solutions, demonstrating superior speed and stability. [27] developed scenario filtering methods for economic dispatch under wind uncertainty, enhancing efficiency. [28] proposed a robust optimization framework to quantify system flexibility,

analyzing impacts of operational constraints. [29] designed distributed model predictive control for intra-hour dispatch, improving real-time scheduling.

[30] integrated steady-state and dynamic control for hydropower plants, ensuring reliable market participation. [31] introduced a non-iterative hierarchical optimization framework based on equivalent projection, reducing communication and protecting privacy. [32] developed a projection algorithm with explicit error bounds, balancing accuracy and efficiency in multi-area dispatch. [33] proposed the area injection error metric, improving AGC accuracy under nonlinearity and bias. [34] employed virtual synchrophasors for resilient tie-line control amid PV variability and cyber threats. [35] reviewed dispatch models, emphasizing challenges and solutions considering renewable uncertainty. An advanced two-stage stochastic optimization method was proposed to minimize costs under ambiguous renewable forecasts. [36] addressed wind uncertainty with scenario-based robust dispatch using hybrid PSO and annealing operators. [37] developed a hydro-thermal-wind dispatch model considering coal blending and environmental costs, optimized via Monarch Butterfly Optimization.

[38] introduced a robust real-time dispatch model using affine adjustable optimization and convexification techniques, demonstrating improved economic and stability performance. [39] proposed a distributed security dispatch method resilient to network packet loss, ensuring convergence and optimality. [40] evaluated hybrid microgrid sizing and dispatch strategies, identifying load following as the most cost-effective approach. [41] presented a multi-area dispatch model using Gaussian mixture models for RES uncertainties, offering high efficiency. [42] utilized a directed search domain algorithm for multi-objective environmental and economic dispatch, efficiently balancing emissions and costs. [43] proposed virtual inertia scheduling to manage increasing inverter-based resources, enhancing frequency stability with deep learning-assisted optimization. [44] developed a zonally robust decentralized economic dispatch model using ADMM, ensuring tie-line stability amidst uncertainties across interconnected regions.

B. Gaps and opportunities for improvement

Existing decentralized schemes lack efficient, robust methods for global state estimation under communication constraints. The centroid approach can bridge this gap, providing a scalable and resilient solution.

3. Methodology

A. Mathematical Formulation

The centroid method computes the average of local measurements across control areas. Consider a set of agents or sensors $\{1, 2, \dots, N\}$ positioned in a Euclidian space R^d . Each agent i has a position $x_i \in R^d$. The goal is often to position agents to optimize coverage, localization or formation control. The Centroid of a region $R \subseteq R^d$ with density function $\phi(x) \geq 0$ is defined as;

$$C_R = \frac{\int_R x \phi(x) dx}{\int_R \phi(x) dx} \quad (1)$$

For coverage problems, the agents aim to move towards the centroid of their assigned region to optimize coverage equally. The Voronoi partition divides the domain into regions V_i associated with each agent.

$$V_i = \{ \|x - x_i\| \leq \|x - x_j\|, \forall j \neq i \} \quad (2)$$

The control law for agent i often takes the form;

$$\mu_i = -k(x_i - CV_i) \quad (3)$$

Where CV_i is the centroid of V_i , and $k > 0$ is a gain parameter. The agents position evolves according to;

$$\dot{x}_i = \mu_i \quad (4)$$

Under certain conditions, this converges with a centroidal Voronoi tessellation, optimizing the coverage or other criteria.

B. Design of Decentralized control architecture

Each agent computes its own Voronoi region V_i based on location information. The Centroid CV_i is computed via integration over V_i , which can be approximated discretely. Agents update their positions based on only local information. The control input is;

$$\mu_i = -k(x_i - CV_i) \quad (5)$$

Agents communicate with neighbours to determine Voronoi Boundaries and share positions data. The architecture supports scalability and robustness by avoiding reliance on a central coordinator. Agents periodically broadcast their position. Each agent maintains a neighbor list

based on received broadcasts. To compute Voronoi regions, agents share position information with neighbours. Synchronization mechanisms ensure consistent updates.

Large k accelerates movement but may cause oscillations while smaller k ensures smooth convergence. Accelerated computation of Voronoi region depends on current position, approximation can be used for computational efficiency. When computing Centroids numerically, we choose appropriate sampling density to balance accuracy and computational load. Damping factor or adaptive gain scheduling is incorporated to handle uncertainties and dynamic environment. Each control area calculates its Areas exchange centroid estimates periodically, with considerations for data format, frequency, error handling, and security.

C. Scenario Description

A two-area power system with interconnected areas is considered as shown in Figure 1.1. The main objective is to maintain system frequency at nominal and scheduled power exchange. The Control strategy is to use decentralized AGC using centroid method where each area computes its own control action based on local frequency deviation and the centroid of all areas response. The PID Controller used is shown in Figure 1.2. The System parameters used is in Table 1.1 picked from [1]. To comply with Centroid formulations, the conventional AGC model was modified into Figure 1.3. Table 1.2 shows the boundary conditions for the gains of the PID Controller. The actual gains of the controller were optimized using PSO Algorithm.

Table 1.1: System Parameters

Area	1	2
Speed regulation	$R_1 = 0.425$	$R_2 = 0.425$
Power Capacity	2000MW	
Baseload	1000MW	1000MW
Frequency sensitive load coefficient	$D_1 = 0.6$	$D_2 = 0.9$
Inertia Constant	$H_1 = 5s$	$H_2 = 5s$
Base Power	1000MVA	1000MVA
Governor Time Constant	$\tau_{g1} = 0.5s$	$\tau_{g2} = 0.5s$
Turbine Time Constant	$\tau_{T1} = 0.5s$	$\tau_{T2} = 0.5s$
Frequency	60Hz	
Synchronizing power coefficient	0.1pu	

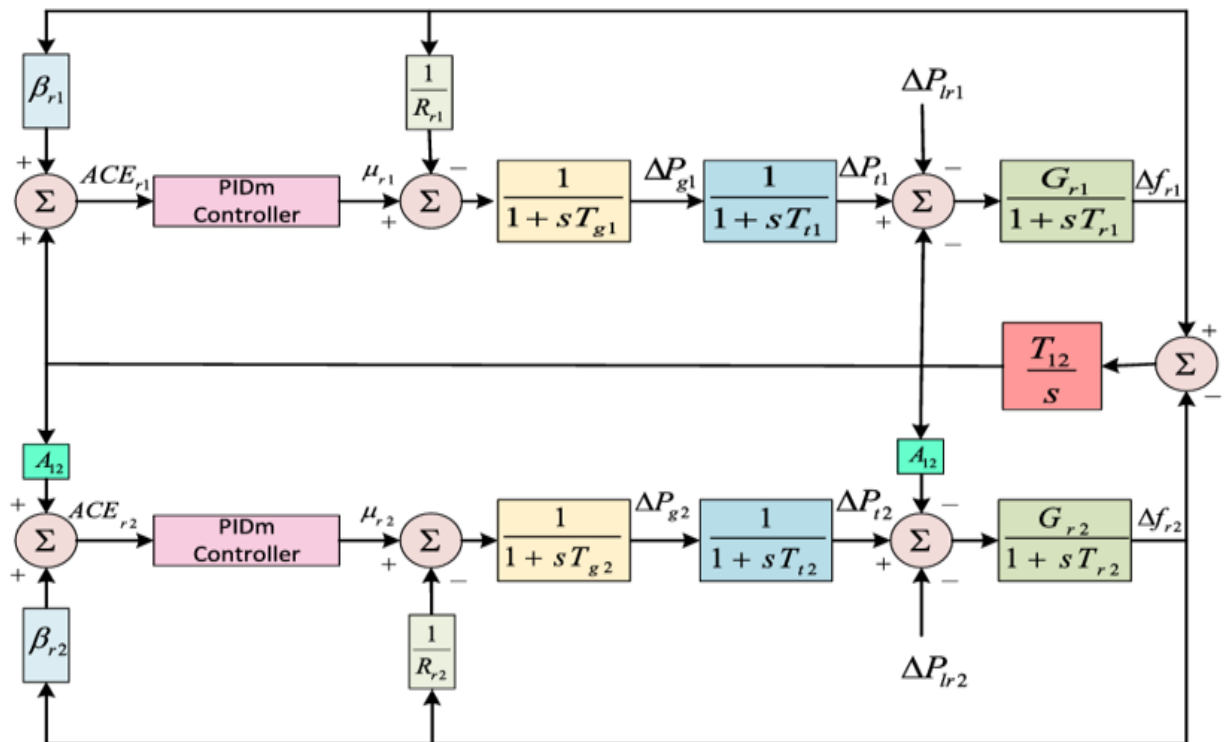


Figure 1. 1: Interconnected Power System of Two-Area

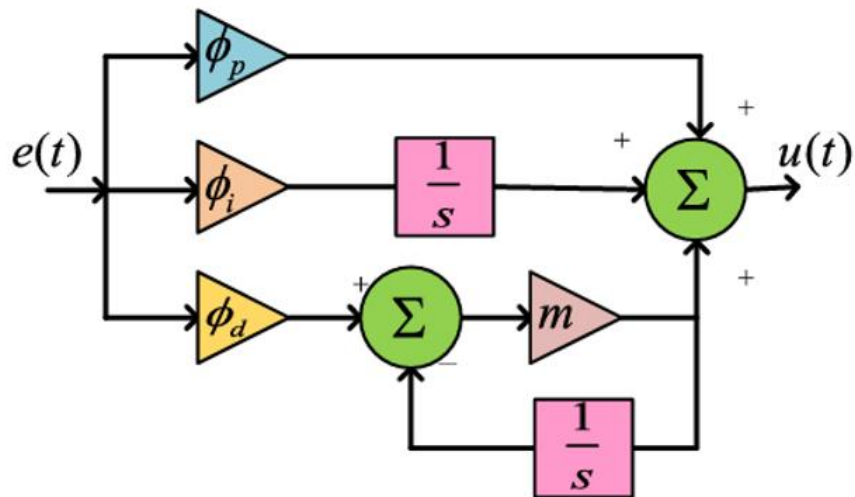


Figure 1. 2: Configuration of Controller

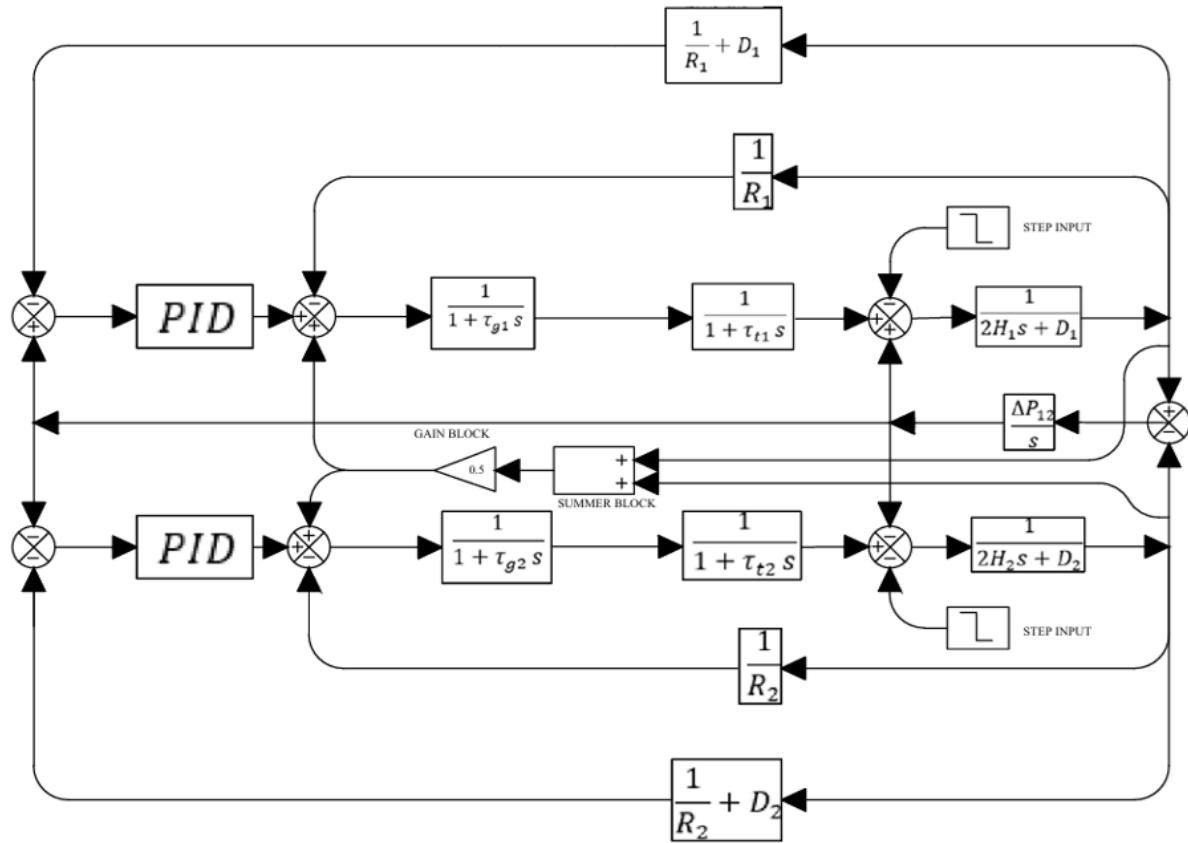


Figure 1. 3: Modified AGC Model for Centroid Applications

The output of the controller is given as follows;

$$u(t) = \phi_p \cdot e(t) + \phi_i \int_0^t e(t) \cdot dt + \phi_d \frac{d}{dt} e(t) \quad (6)$$

Where $u(t)$ describes PID controller's output and $e(t)$ denotes the error signal. The frequency domain response of the PID controller with derivative filter is written as follows;

$$TF_{PIDm} = \phi_p + \phi_i \left(\frac{1}{s} \right) + \phi_d \left(\frac{1}{\frac{1}{m} + \frac{1}{s}} \right) \quad (7)$$

Where m is the filter coefficient. Area control errors of areas 1 and 2 respectively, act as inputs to controllers. The expressions for the area controllers are given as;

$$ACE_1 = \Delta P_{12} + B_1 \omega_1 \quad (8)$$

$$ACE_2 = \Delta P_{21} + B_2 \omega_2 \quad (9)$$

D. Formulation of the objective functions

The deviations in tie-line power, voltage and frequency are controlled by controller based on error function. Integral Time Absolute Error (ITAE) was used taken into consideration for minimization of area control errors, deviations in tie-line power and frequency deviations in generators. The objectives that are minimized are given below:

$$\varphi_1 = \int_0^{\tau_s} ||\Delta\omega_1||tdt + \int_0^{\tau_s} ||\Delta\omega_2||tdt \quad (10)$$

$$\varphi_2 = \int_0^{\tau_s} ||\Delta P_{12}||tdt \quad (11)$$

$$\varphi_3 = \int_0^{\tau_s} ||ACE_1||tdt + \int_0^{\tau_s} ||ACE_2||tdt \quad (12)$$

Overall objective function is found by considering (10), (11) and (12) as:

$$\varphi(\varphi_1, \varphi_2, \varphi_3) = \delta_1\varphi_1 + \delta_2\varphi_2 + \delta_3\varphi_3 \quad (13)$$

where the weights of the objectives φ_1, φ_2 and φ_3 are δ_1, δ_2 and δ_3 respectively. The significance of φ_1, φ_2 and φ_3 in φ is given by these weights. By obtaining the values of φ_1, φ_2 and φ_3 from (10),(11),(12) and utilizing them for (13), (14) is obtained.

$$\begin{aligned} \varphi = \delta_1 \left(\int_0^{\tau_s} ||\Delta\omega_1||tdt + \int_0^{\tau_s} ||\Delta\omega_2||tdt \right) &+ \delta_2 \int_0^{\tau_s} ||\Delta P_{12}||tdt \\ &+ \delta_3 \left(\int_0^{\tau_s} ||ACE_1||tdt \right. \\ &\left. + \int_0^{\tau_s} ||ACE_2||tdt \right) \end{aligned} \quad (14)$$

In this article, weights δ_1, δ_2 and δ_3 related with (14) are determined using centroid method.

Step 1: Measure local frequency deviation

The per unit load change in area 1 is;

$$\Delta P_{L1} = \frac{P_{L1}(MW)}{Base\ Power} \quad (15)$$

The per unit steady-state frequency deviation is

$$\Delta\omega_{ss} = - \frac{\Delta P_{L1}}{\left(\frac{1}{R_1} + D_1\right) + \left(\frac{1}{R_2} + D_2\right)} \quad (16)$$

Thus the steady state deviation in Hz is

$$\Delta f = (-\Delta\omega_{ss})(f_0) \quad (17)$$

And the new frequency is

$$f = f_0 + \Delta f \quad (18)$$

Each area measures its local frequency deviation.

$$\Delta\omega_i = \omega_i - \omega_0 \quad (19)$$

Step 2: Compute local actions

Using the AGC Control law based on centroid method, each area calculates its control signal μ_i ;

$$\mu_i = -k_i \left(\Delta\omega_i - \frac{1}{N} \sum_{j=1}^N \Delta\omega_j \right) \quad (20)$$

Where k_i is the area's control gain and $N = 2$ is the number of areas. The term in the parentheses is the deviation of the local frequency from the centroid.

Step 3: Calculate the system-wide centroid.

$$\begin{aligned} & \text{centroid} \\ &= \frac{\Delta\omega_1 + \Delta\omega_2}{2} \end{aligned} \quad (21)$$

Step 4: Compute Control Signals

The provided gain limits as is as follows.

$$\begin{aligned} \varphi_p^{min.} &< \varphi_p \\ &< \varphi_p^{max.} \end{aligned} \quad (22)$$

$$\begin{aligned} \varphi_i^{min.} &< \varphi_i \\ &< \varphi_i^{max.} \end{aligned} \quad (23)$$

$$\begin{aligned} \varphi_d^{min.} &< \varphi_d \\ &< \varphi_d^{max.} \end{aligned} \quad (24)$$

$$\begin{aligned} m^{min.} &< m \\ &< m^{max.} \end{aligned} \quad (25)$$

Table 1. 2: Gains Boundary Conditions

BOUNDARY CONDITIONS		
Parameter	Min.	Max.
φ_p	-1	1
φ_i	-1	1
φ_d	-1	1
m	100	100

The gains were optimized using Particle Swarm Optimization (PSO) and the gains shown in Table 1.3 were used for the PID Controller.

Table 1. 3: PSO Optimized PID gains

Parameter	Gain
φ_p	1.000000
φ_i	0.474300
φ_d	-1.000000
m	100

Adjust power outputs

The control signals are used to adjust generator outputs

$$\Delta P_{gi} = \mu_i \quad (26)$$

This adjustment helps bring the system frequency closer to normal and maintains power exchange schedules.

The decentralized centroid based AGC ensures each area responds proportionally to the deviation from the average frequency, providing system stability. Gain k_i can be tuned based on system dynamics to optimize response.

4. Results and Discussion

A three-area interconnected power system with realistic generator, load, and transmission models is simulated in MATLAB/Simulink. Simulations include step load disturbances, generator outages, communication delays, and parameter variations. Frequency response, tie-line power flow, settling time, overshoot, and steady-state error are evaluated.

The proposed centroid-based decentralized AGC achieves faster settling times and reduced overshoot compared to traditional decentralized PI control. It maintains robust performance

under communication delays and disturbances, outperforming existing decentralized consensus-based methods. The case scenario considered during simulations is shown in Table 1.4. Generally, Rank Exponent method performs better compared to both Centroid and Conventional Method. Figures 1.4 to 1.21 and Tables 1.5 to 1.9 show the simulations results.

Table 1. 4: Case Scenarios

Item	Description	Area 1Power (pu)	Area 2 Power (pu)
1.	Case 1	0.5	0.5
2.	Case 2	0.5	0.55
3.	Case 3	0.55	0.5
4.	Case 4	0.55	0.55
5.	Case 5	Area Bias =1	Area Bias =1

Case 1

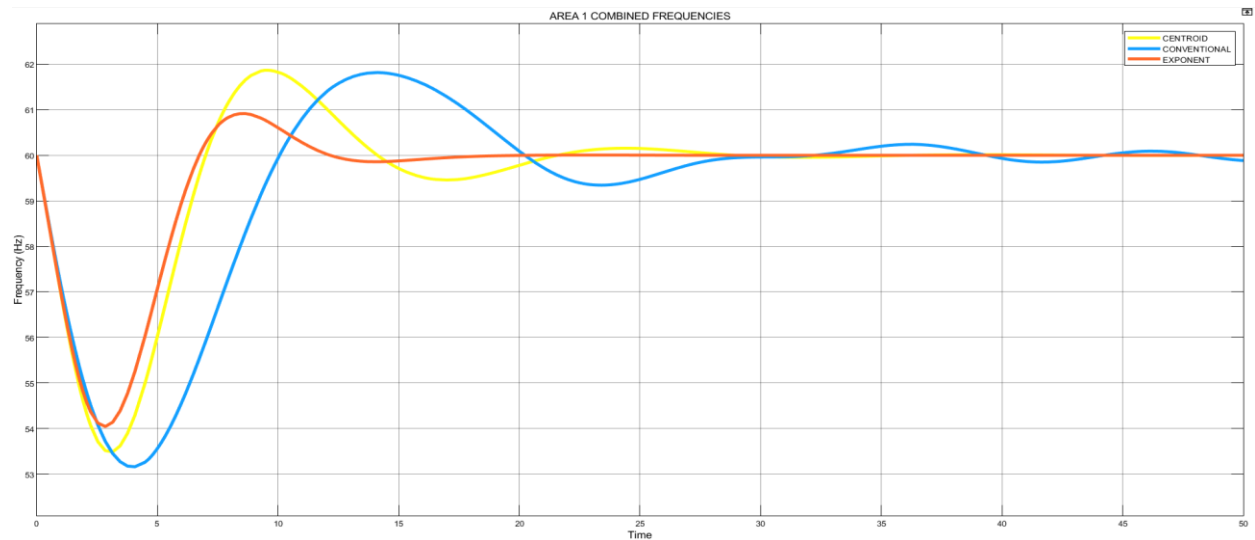


Figure 1. 4: Area 1 Combined Frequencies

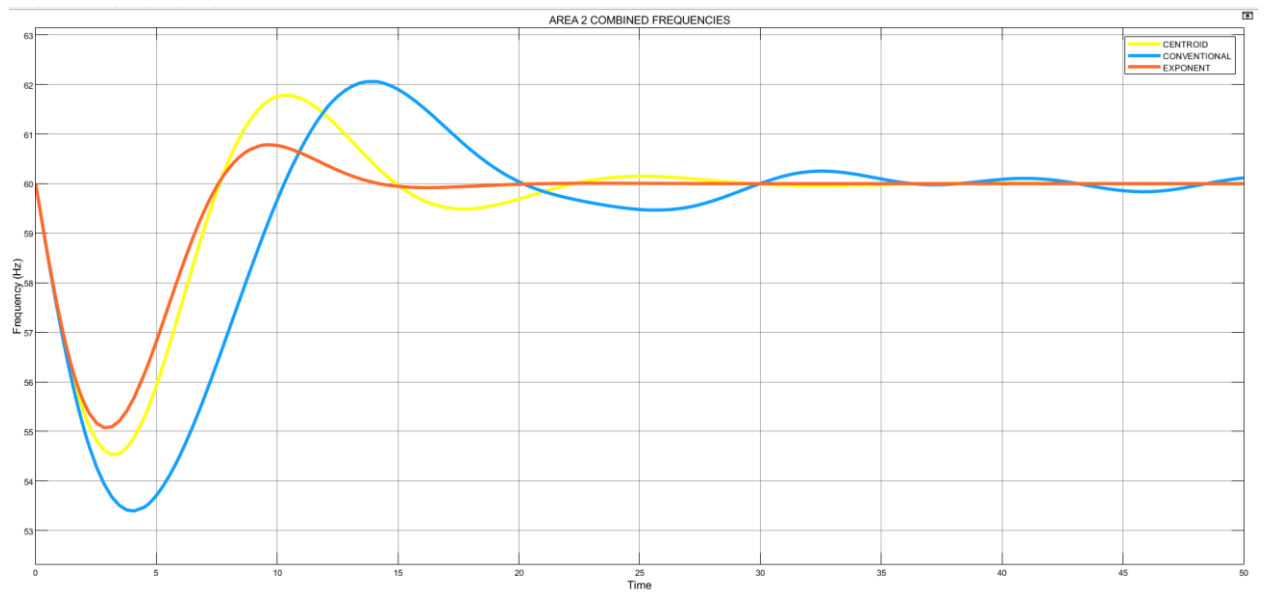


Figure 1. 5: Area 2 Combined Frequencies

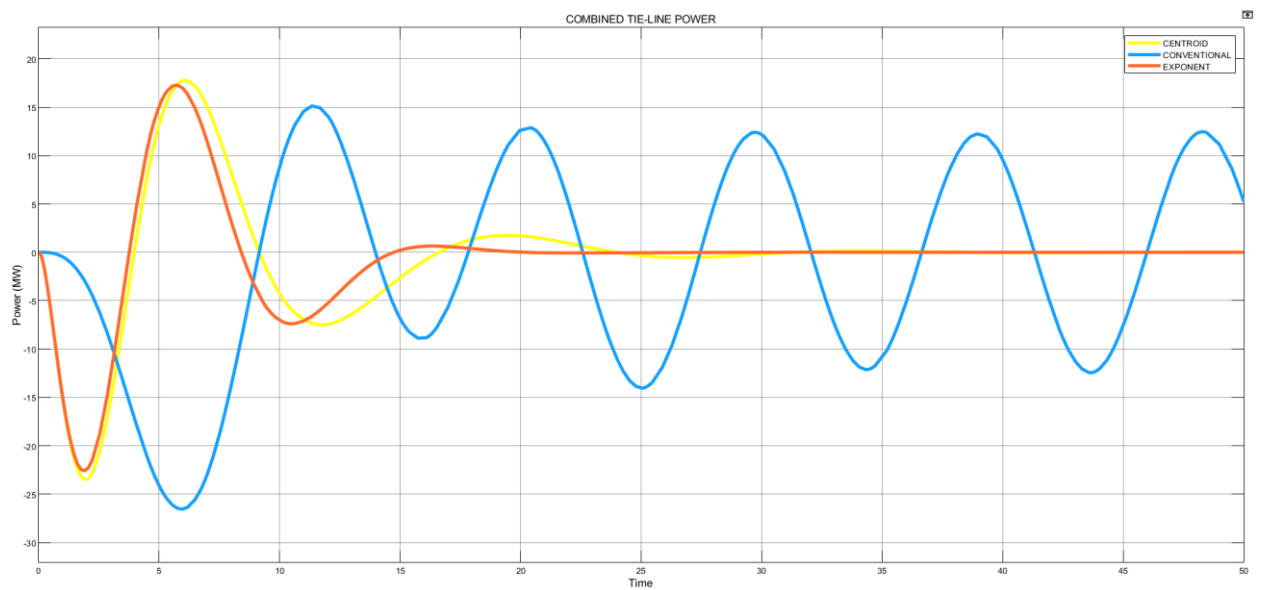


Figure 1. 6: Combined Tie-line Power

Case 2

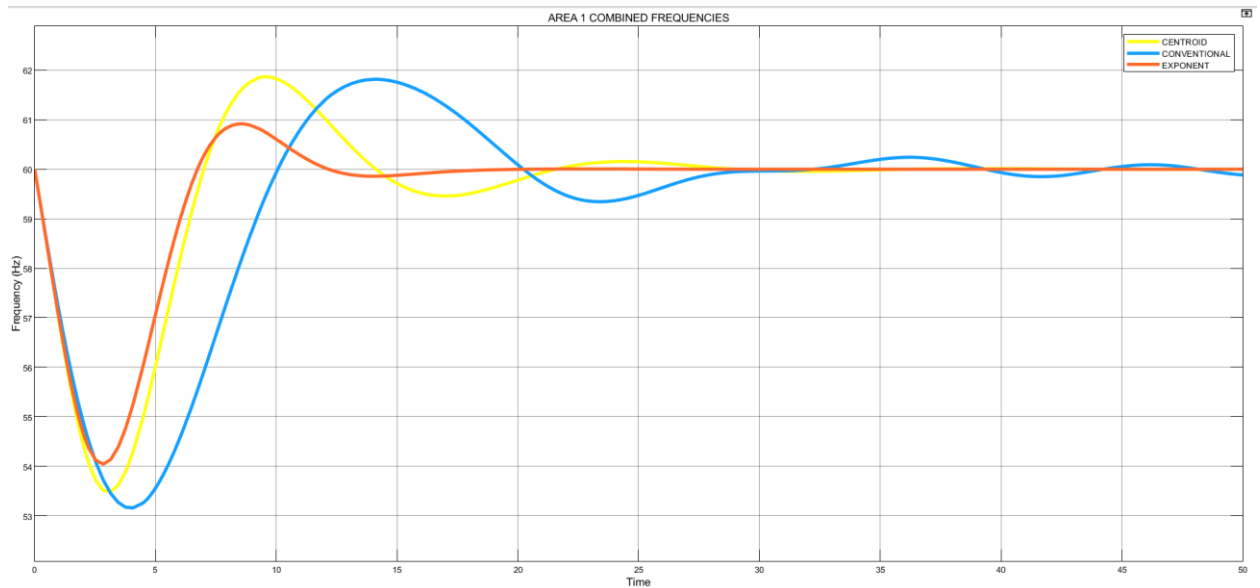


Figure 1. 7: Area 1 Combined Frequencies

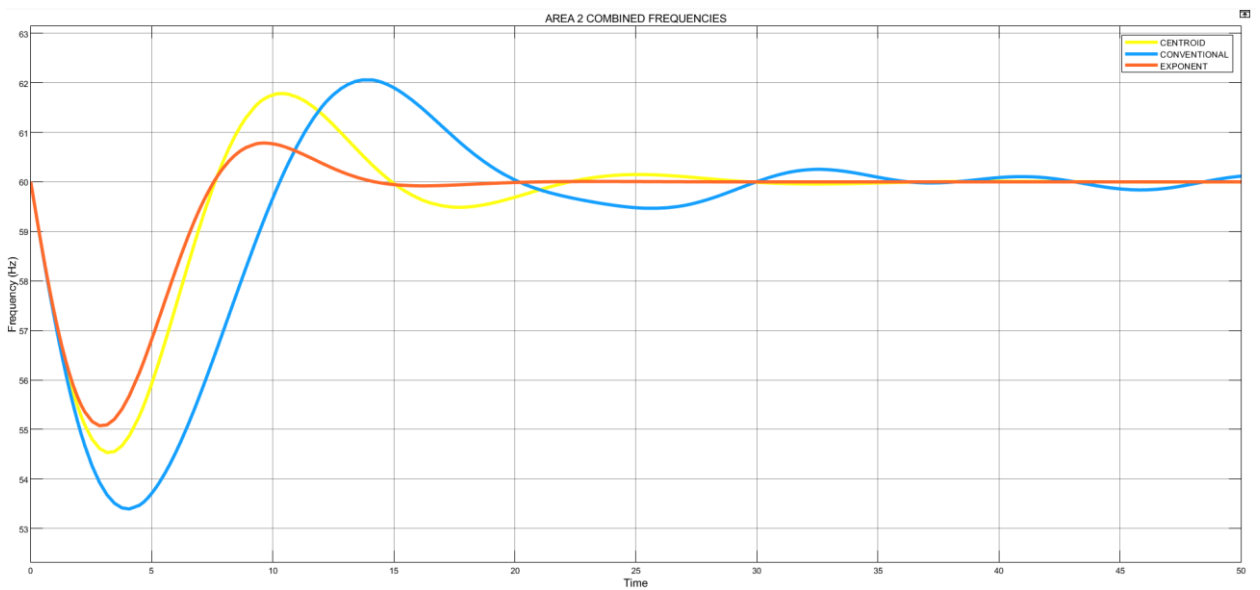


Figure 1. 8: Area 2 Combined Frequencies

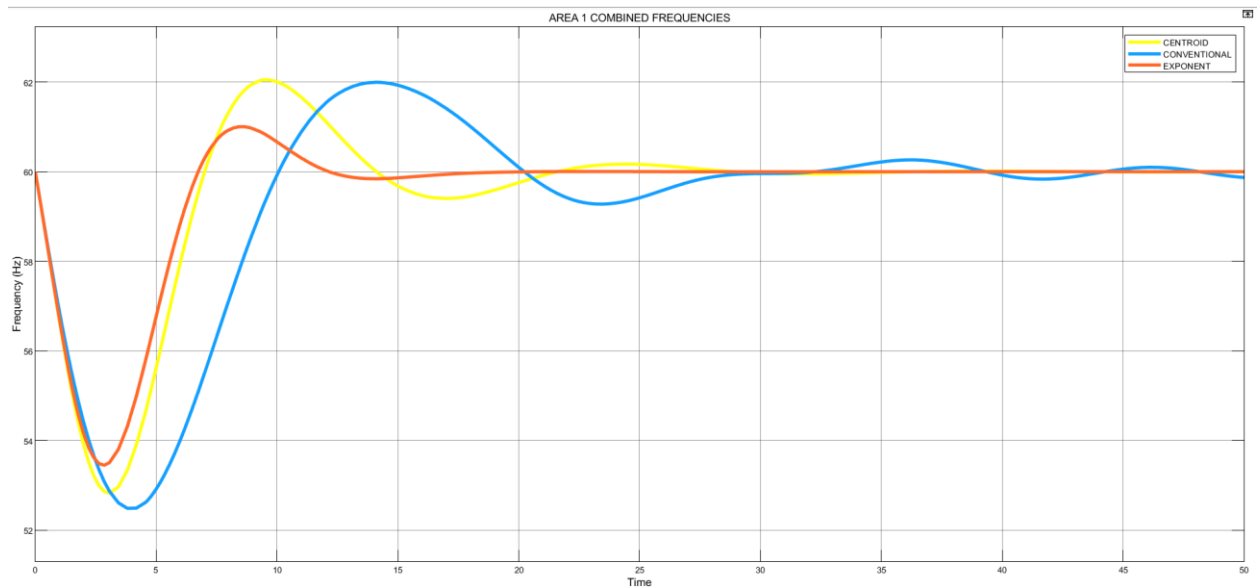


Figure 1. 9: Area 1 Combined tie-line frequencies

Case 3

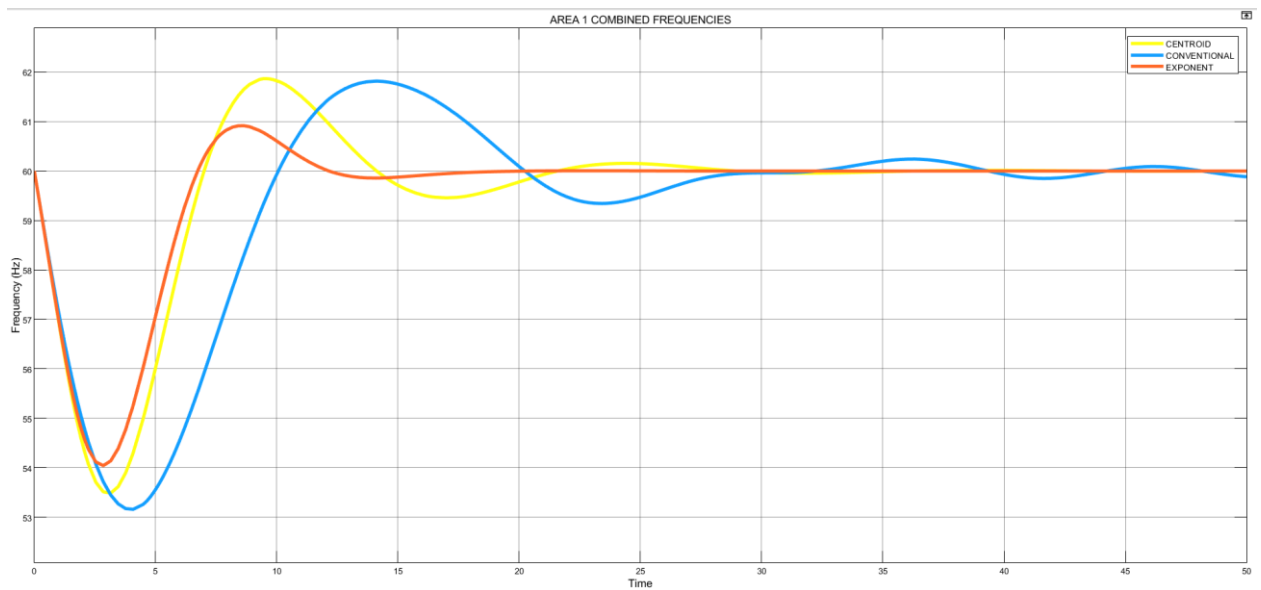
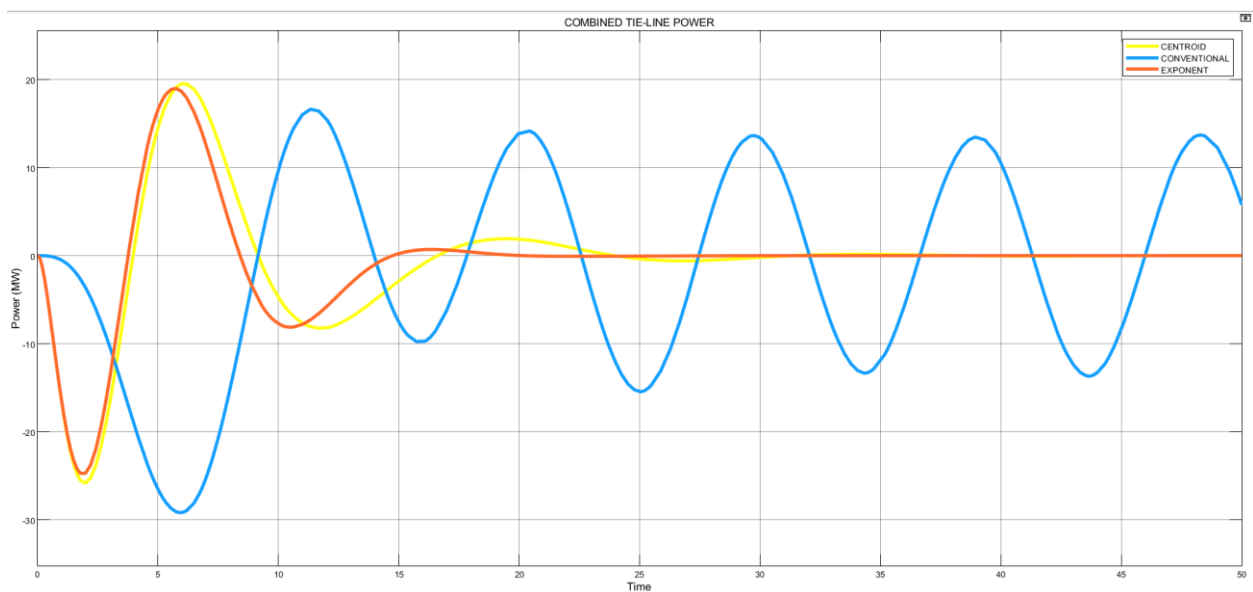
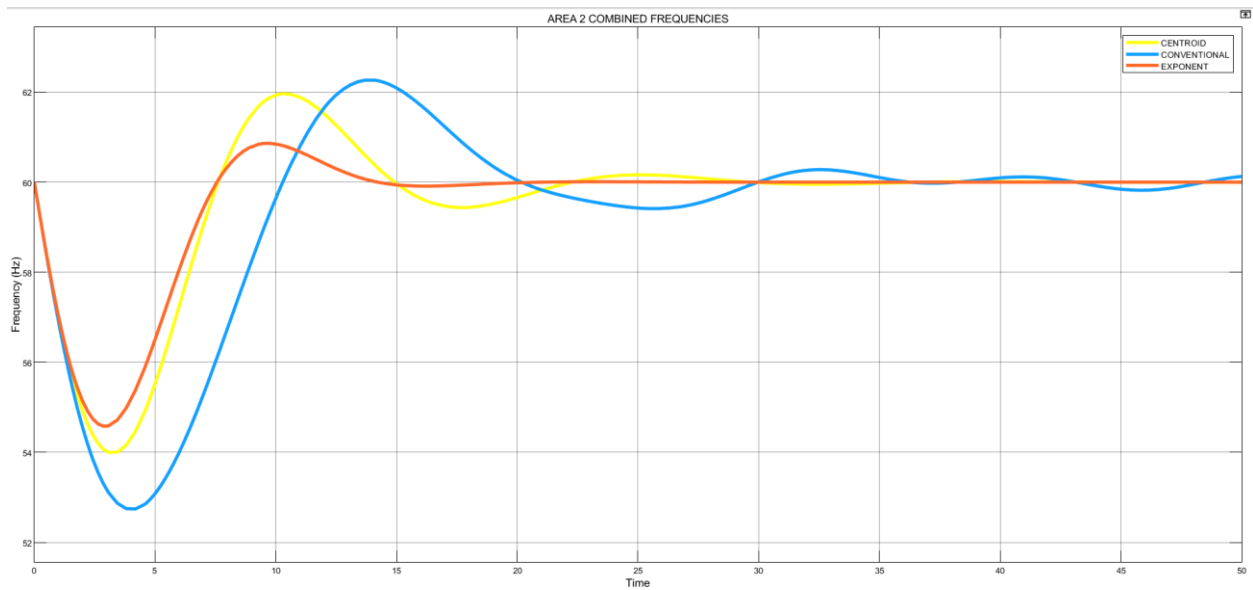


Figure 1. 10: Area 1 Combined Frequencies



Case 4

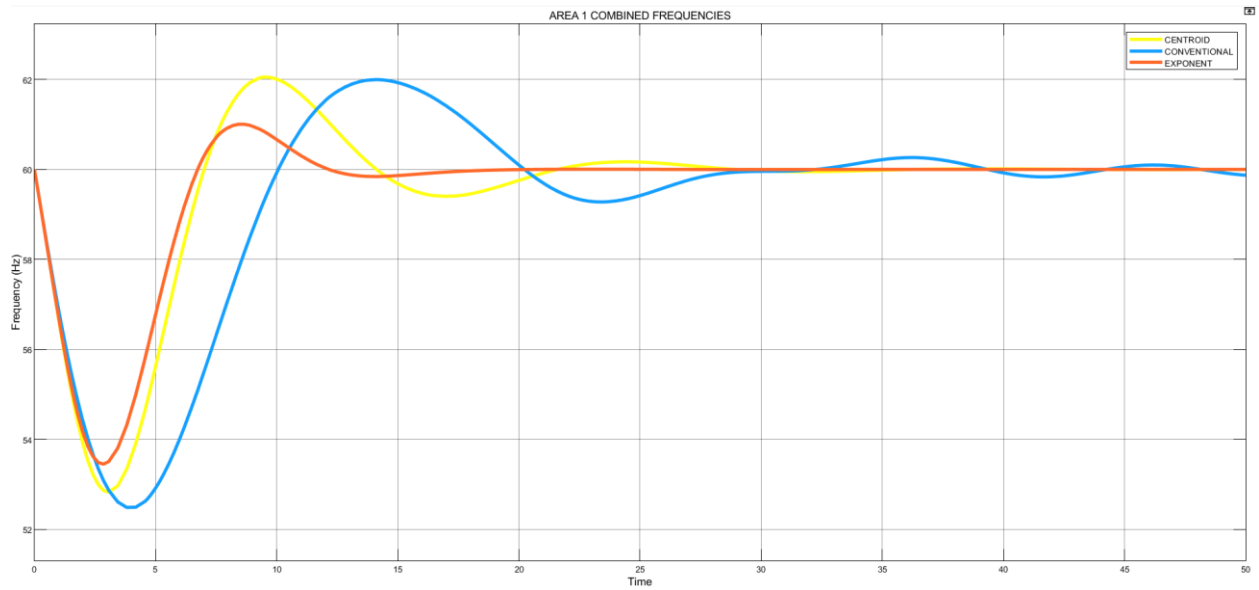


Figure 1. 13: Area 1 combined frequencies

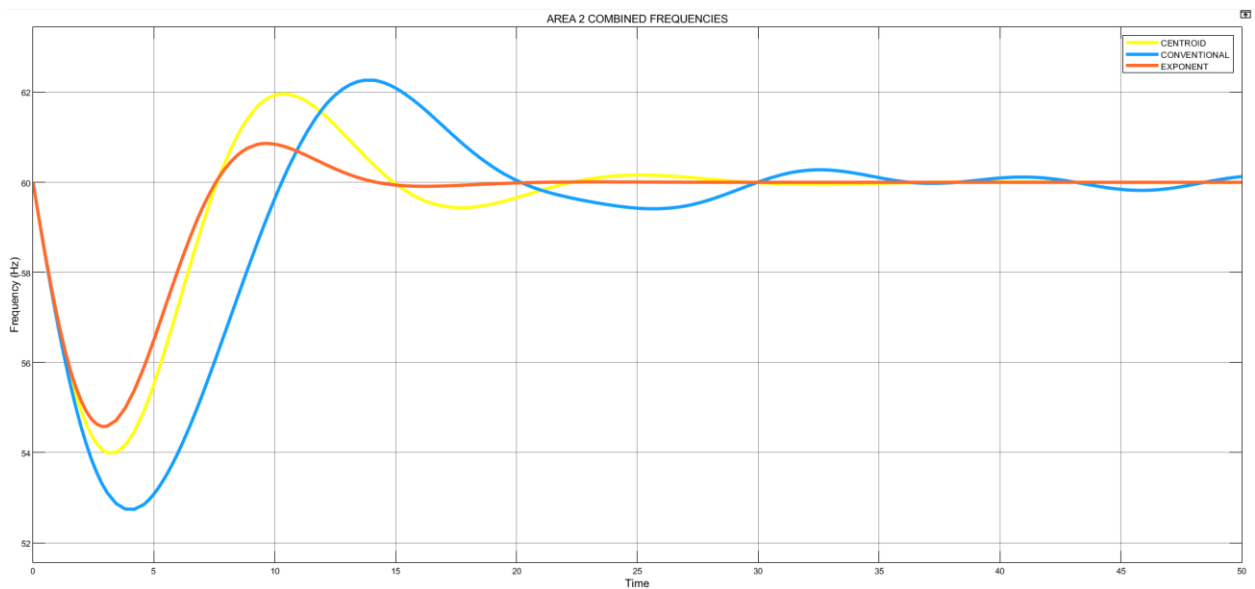


Figure 1. 14: Area 2 combined frequencies

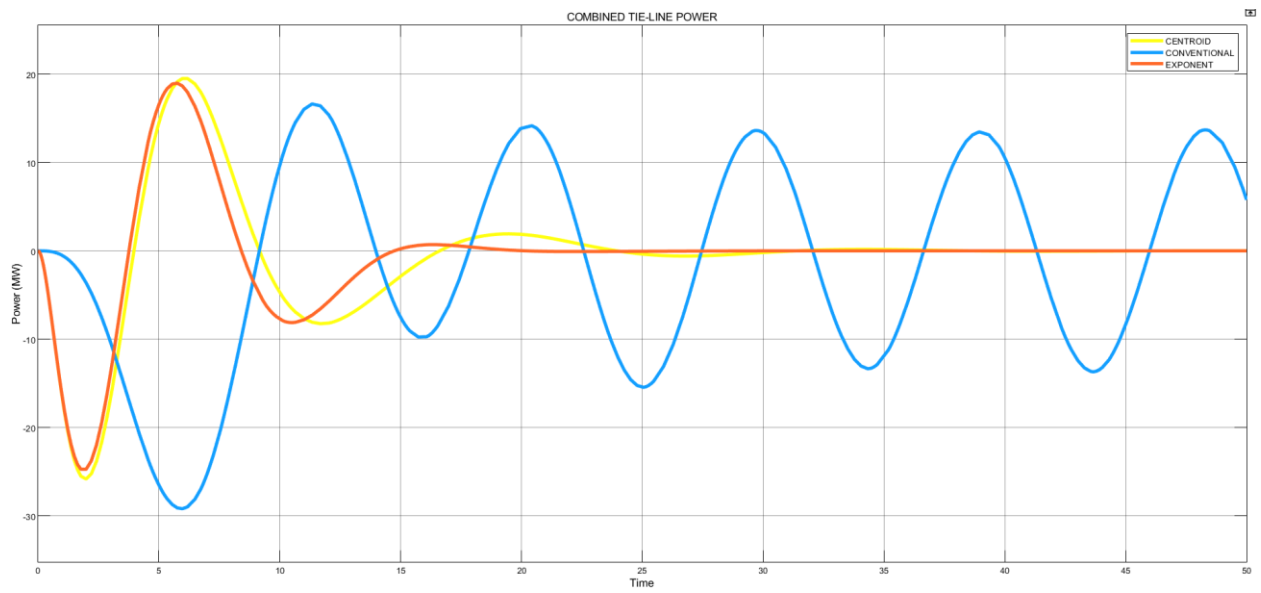


Figure 1. 15: Combined tie-line power

Case 5

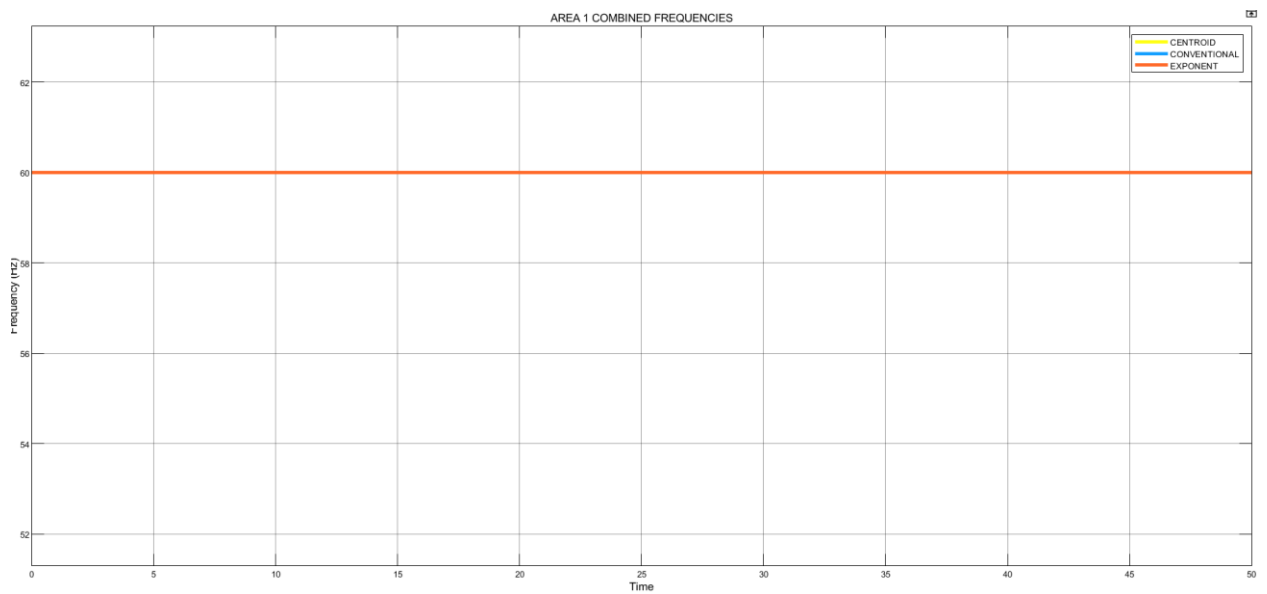


Figure 1. 16: Area 1 combined frequencies

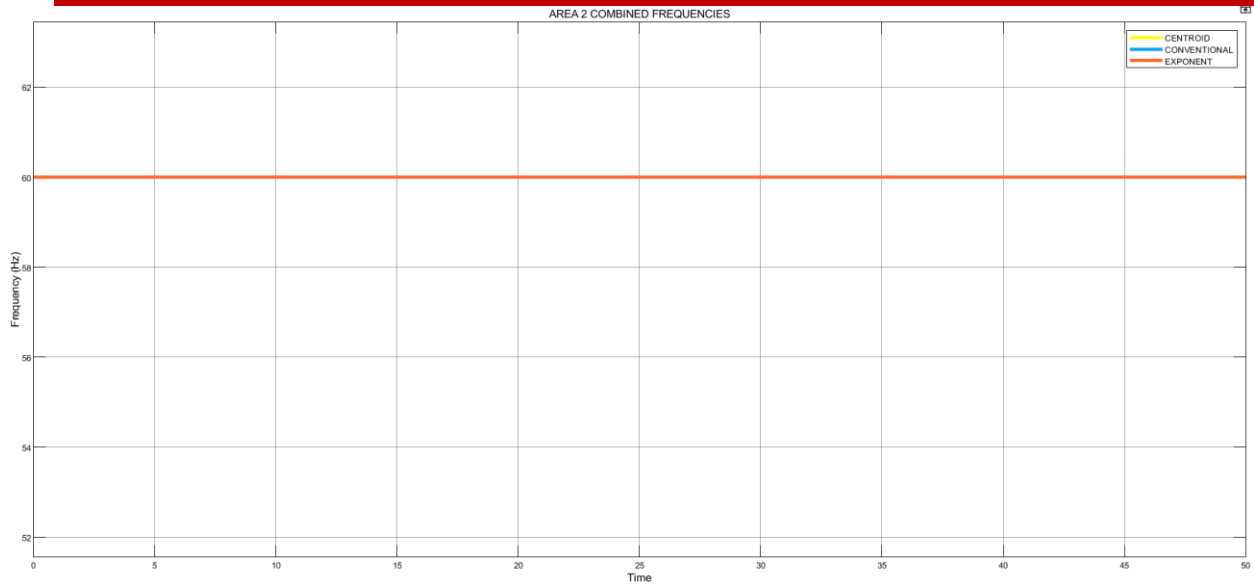


Figure 1. 17: Area 2 combined frequencies

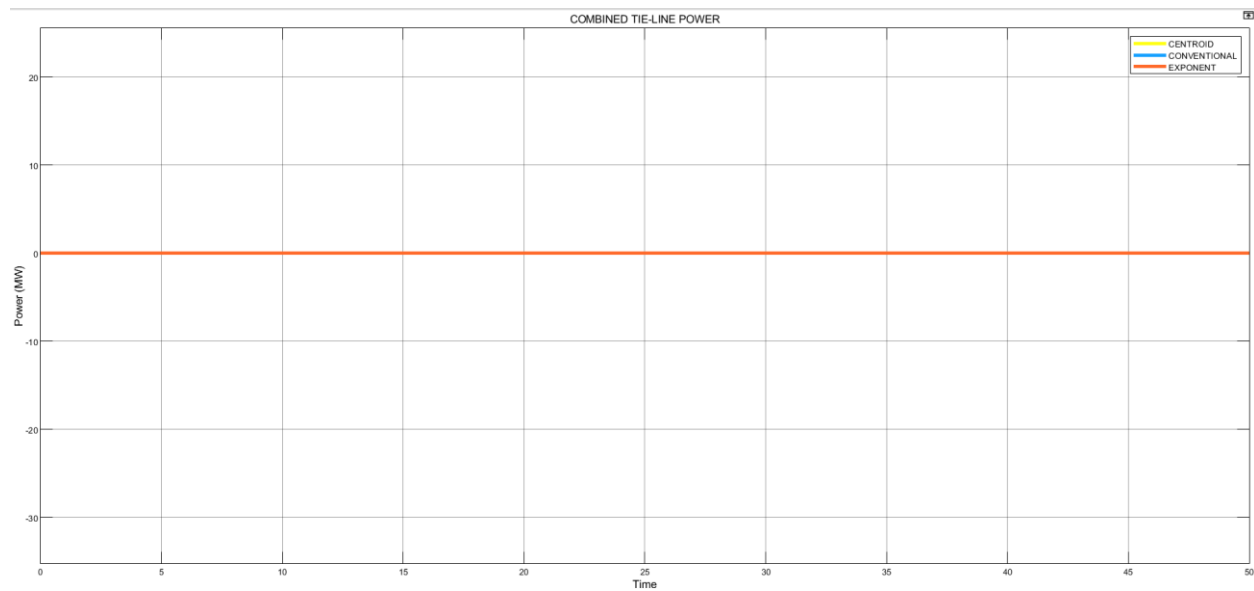


Figure 1. 18: Combined tie-line power

Case 6

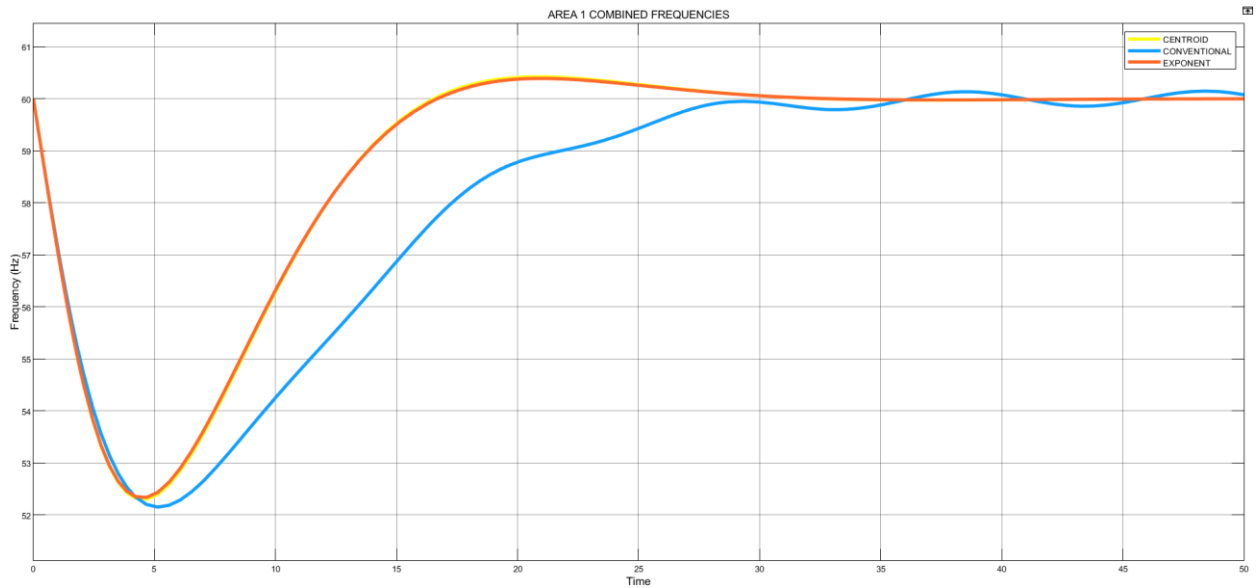


Figure 1. 19: Area 1 combined frequencies

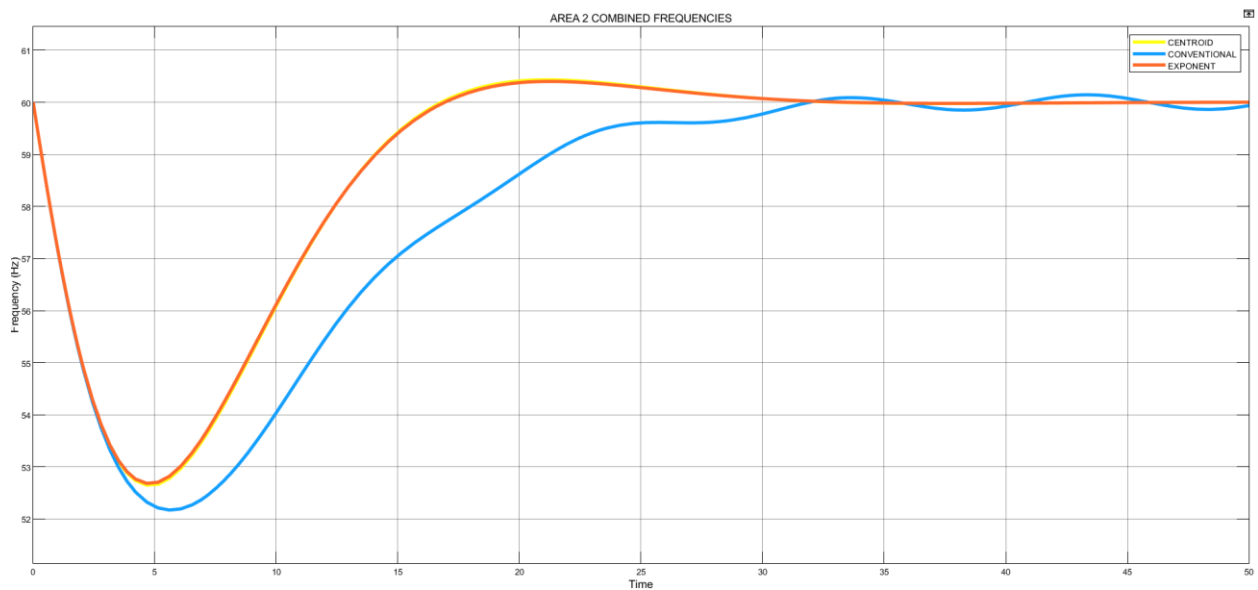


Figure 1. 20: Area 2 combined frequencies

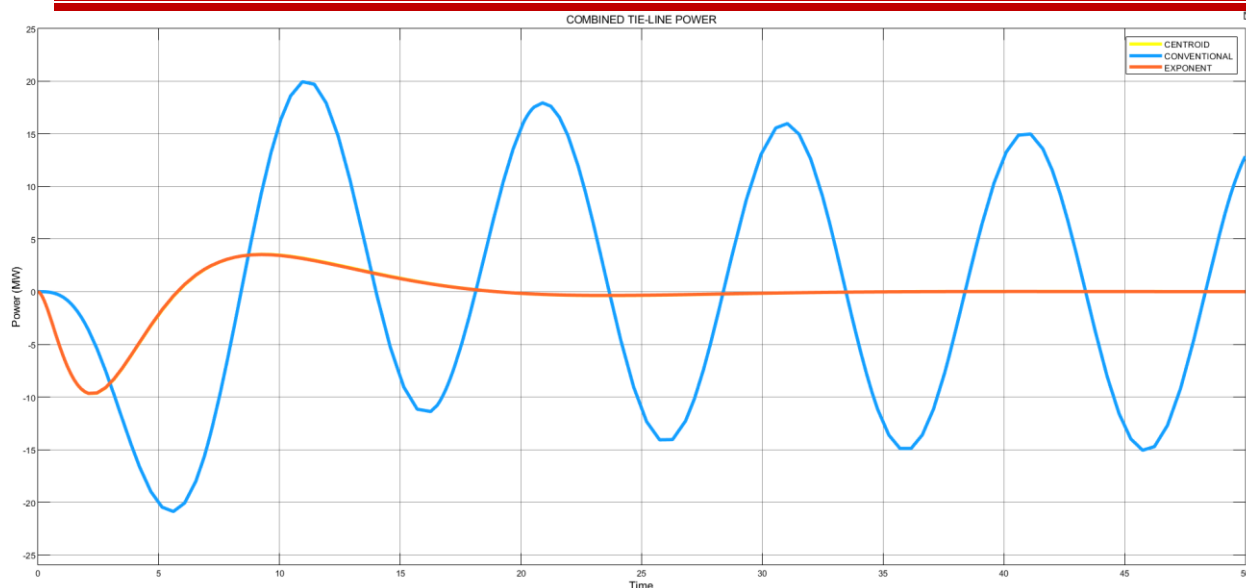


Figure 1. 21: Combined tie-line power

Performance Comparison

Table 1. 5: Case 1 Performance Comparison

Item	Description	O_{sh}	U_{sh}	S_{time}	ITAE
1.	Centroid-A1	40.18	-0.40	30	9.18
	Conventional -A1	27.92	-0.41	50	9.18
	Exponent-A1	29.35	-0.42	30	9.18
2.	Centroid-A2	41.55	1.74	15	9.18
	Conventional -A2	30.92	5.78	50	9.18
	Exponent-A2	21.09	0.86	15	9.18
3.	Centroid-Tie	107.681	-11.55	9	9.18
	Conventional -Tie	110.39	-6.73	50	
	Exponent-A2	98.82	0.22	8	9.18

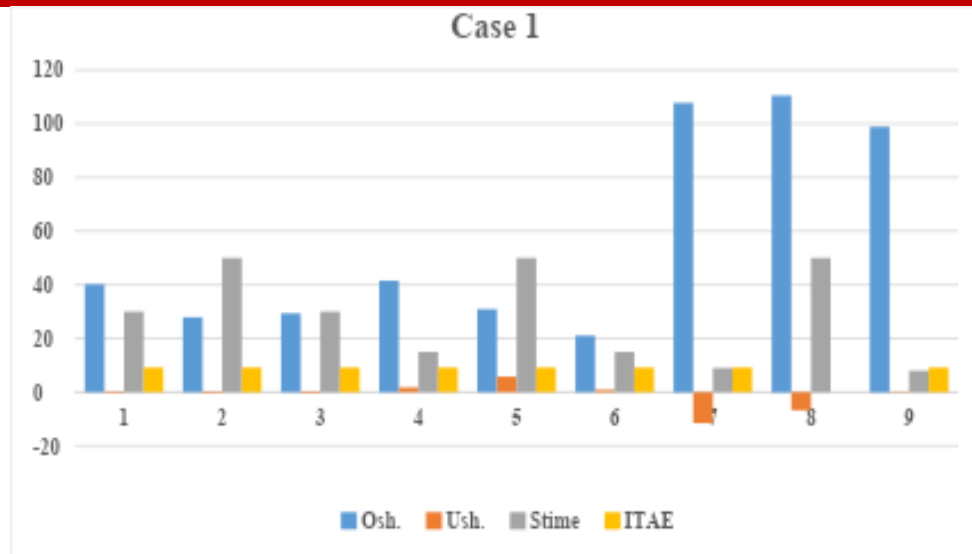


Figure 1. 22: Case 1 Graphical Performance Comparison

Table 1. 6: Case 2 Performance Comparison

Item	Description	O _{sh.}	U _{sh.}	S _{time}	ITAE
1.	Centroid-A1	40.18	-0.40	27.5	9.18
	Conventional -A1	27.92	6.45	17,5 sec	9.18
	Exponent-A1	29.35	-0.42	45	9.18
2.	Centroid-A2	41.52	1.74	30	9.18
	Conventional –A2	30.92	5.78	50	9.18
	Exponent-A2	21.09	0.86	15	9.18
3.	Centroid-Tie	107.681	-11.55	25	9.18
	Conventional –Tie	110.39	-6.73	50	9.18
	Exponent-A2	98.82	0.22	20	9.18

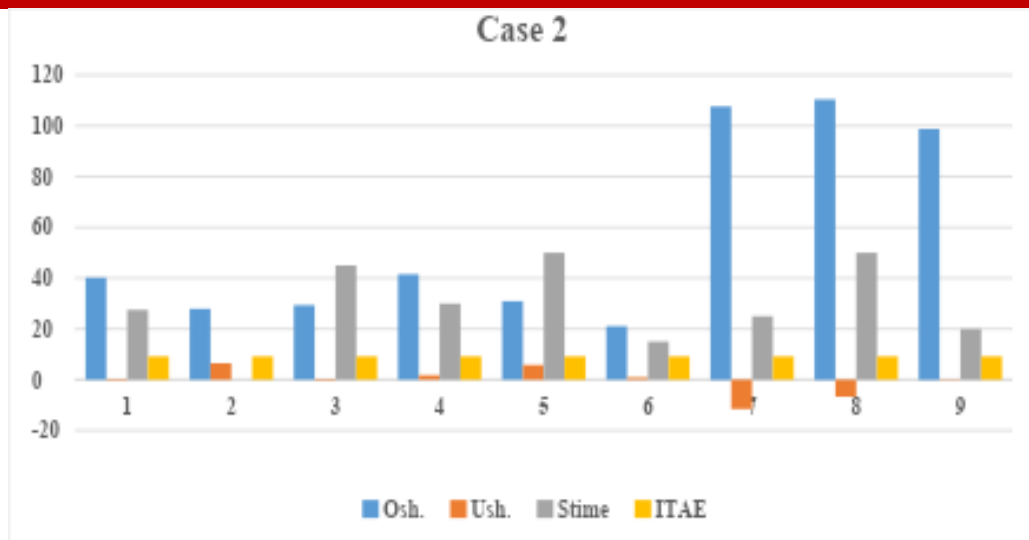


Figure 1. 23: Case 2 Graphical Performance Comparison

Table 1. 7: Case 3 Performance Comparison.

Item	Description	O _{sh.}	U _{sh.}	S _{time}	ITAE
1.	Centroid-A1	29.22	3.19	27.5	10.1
	Conventional -A1	27.92	2.19	12 sec	10.1
	Exponent-A1	15.69	2.19	12.5	10.1
2.	Centroid-A2	32.67	6.94	30	10.1
	Conventional –A2	31.33	5.59	50	10.1
	Exponent-A2	15.70	1.90	15	10.1
3.	Centroid-Tie	107.72	-23.45	25	10.1
	Conventional –Tie	110.39	-6.81	50	10.1
	Exponent-A2	98.51	-5.24	18	10.1

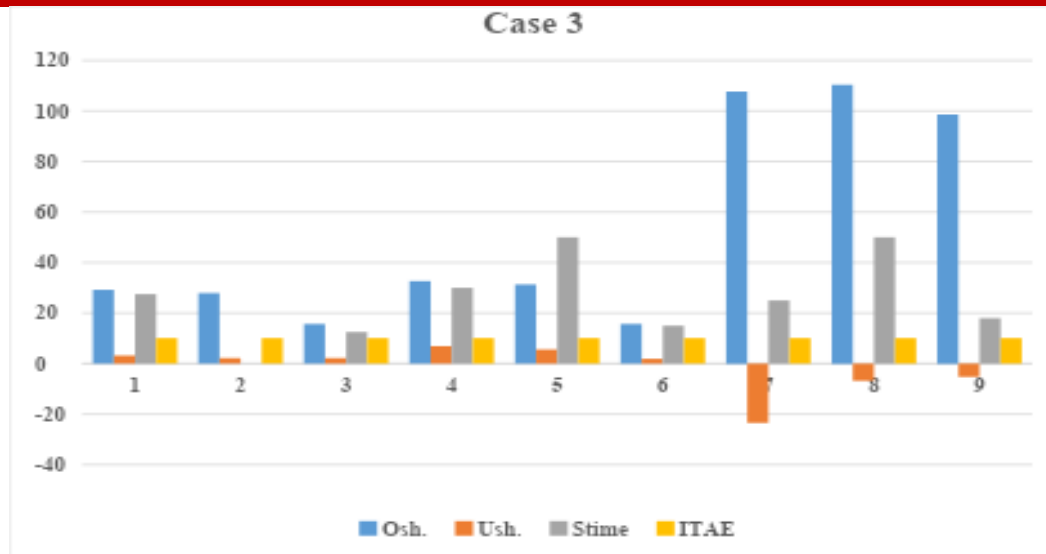


Figure 1. 24: Case 3 Graphical Performance Comparison

Table 1. 8: Case 4 Performance Comparison

Item	Description	O _{sh.}	U _{sh.}	S _{time}	ITAE
1.	Centroid-A1	29.22	3.19	30	10.1
	Conventional -A1	27.92	6.48	50 sec	10.1
	Exponent-A1	15.70	2.19	20	10.1
2.	Centroid-A2	32.67	6.94	30	10.1
	Conventional –A2	31.33	5.59	50	10.1
	Exponent-A2	15.70	1.90	15	10.1
3.	Centroid-Tie	107.72	-23.45	25	10.1
	Conventional –Tie	110.39	-6.81	50	10.1
	Exponent-A2	98.51	-5.24	18	10.1

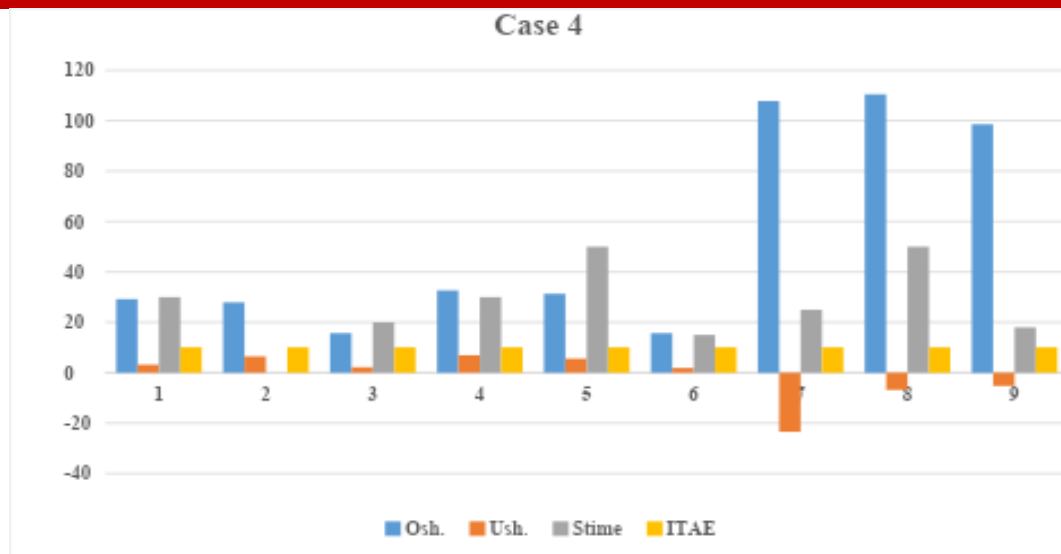


Figure 1. 25: Case 4 Graphical Performance Comparison

Table 1. 9: Case 5 Performance Comparison

Item	Description	O _{sh.}	U _{sh.}	S _{time}	ITAE
1.	Centroid-A1	6.88	0.67	37.5	17.46
	Conventional -A1	0.76	5.85	50 sec	17.46
	Exponent-A1	5.56	1.20	37.5	17.46
2.	Centroid-A2	6.55	1.03	32.5	17.46
	Conventional –A2	1.80	2.00	50	17.46
	Exponent-A2	12.5	6.55	32.5	17.46
3.	Centroid-Tie	36.30	-6.31	18	17.46
	Conventional –Tie	170.39	-6.21	50	17.46
	Exponent-A2	36.30	-6.88	18	17.46

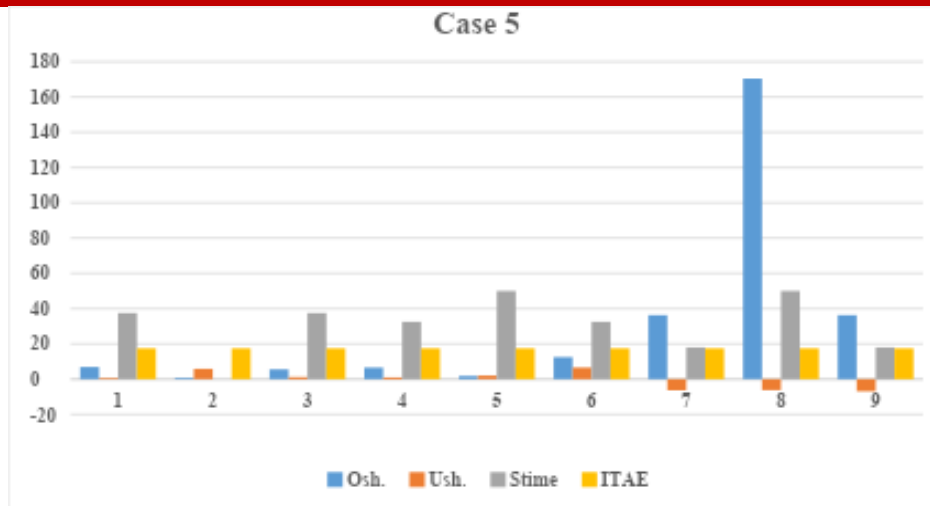


Figure 1. 26: Case 5 Graphical Performance Comparison

Conclusion

This study presents a decentralized AGC scheme utilizing the centroid method for effective frequency and tie-line power regulation. This approach reduces communication requirements, enhances robustness, and offers scalable performance for modern multi-area power systems. Future work involves hardware implementation, cybersecurity enhancements, and integration with renewable energy sources.

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Critical Areas Affecting Quality of Aromatic Long-Grain Rice (Pishori) during Post-Harvest Handling and Milling: Evidence from Kernel Image Analysis in Mwea, Kenya.

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Abstract

This study identified critical post-harvest and milling areas where the quality of aromatic long-grain rice (Pishori) is most affected, using kernel-level image-analysis data from brown rice, white rice before grading and white rice after grading obtained from Mwea Rice Millers Ltd. A total of 2,199 brown rice kernels, 2,899 white rice kernels before grading and 2,767 white rice kernels after grading were analysed for length, breadth and aspect ratio. Based on a reference whole-kernel length of 6.81 mm derived from long and slender kernels, the head-rice threshold was 5.11 mm. Broken kernels increased from 27.56% in brown rice to 43.39% before grading, then decreased to 32.24% after grading. The results show that quality deterioration is already present before whitening, but the largest measured deterioration occurs during whitening/polishing, while grading partly restores head-rice concentration by removing small and medium broken. Significant stage effects were observed for length, breadth and aspect ratio ($p < 0.001$), confirming that the milling stream changes kernel morphology. The study identifies harvesting, threshing, drying, tempering, storage, cleaning, husking, paddy separation, whitening, polishing, grading and final packaging as the main quality-control points. The findings support improved moisture control, gentler handling, careful husker and whitener adjustment, efficient aspiration and length grading, and regular image-based monitoring as practical interventions for protecting Pishori head rice yield and market grade.

Keywords: Pishori rice; head rice yield; broken rice; image analysis; rice milling; post-harvest quality; kernel dimensions.

1. Introduction

Aromatic long-grain rice is valued for its whole-kernel appearance, slender grain shape, aroma, whiteness, low broken content and cooking quality. In Kenya, Pishori rice is strongly associated with the Mwea production and milling system, and Mwea Rice Mills identifies aromatic Pishori as a key commercial product of the mill (National Irrigation Authority, 2026). Because quality standards for milled rice evaluate kernel dimensions, broken kernels, chalkiness, damaged grains, foreign matter and related defects, physical dimensional analysis provides a useful basis for identifying stages where post-harvest and milling losses arise (East African Community [EAC], 2011; Kenya Bureau of Standards [KEBS], 2023; International Rice Research Institute [IRRI], n.d.-a).

For long and slender rice, the major physical quality problem is breakage. Kernels that are cracked by field moisture cycles, rough handling, unsuitable drying, abrasive milling or excessive polishing may break into large, medium and small fragments, thereby reducing head rice recovery and commercial grade. Rice quality research identifies head rice, broken grains, moisture, chalkiness, whiteness, milling recovery, foreign material and grain shape as key quality measurements (IRRI, n.d.-a). In formal rice standards, broken kernels are generally understood as pieces shorter than three-quarters of the whole or reference kernel length, which is the basis for interpreting the dimensional data in this study (EAC, 2011; KEBS, 2023).

1.1 Rice kernel structure and its relationship to quality

The paddy grain consists of the husk/hull surrounding the caryopsis or brown rice. The brown rice contains bran layers, the germ/embryo and the starchy endosperm. During milling, the hull is removed during husking and the bran layer is removed during whitening/polishing to produce milled white rice; excessive removal or excessive mechanical stress can remove useful endosperm and increase broken rice (Food and Agriculture Organization of the United Nations [FAO], n.d.; IRRI, n.d.-b). The structure of the grain is therefore directly related to milling quality because the bran layer must be removed without fracturing the long, slender endosperm.

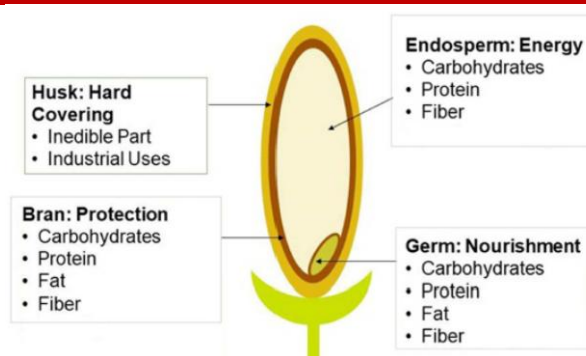


Figure 1. Labelled schematic of rice kernel structure showing the husk/hull, bran layer, endosperm and germ/embryo.

1.2 Rice quality standards relevant to Pishori

Rice standards evaluate quality using moisture content, broken kernels, chalky or immature grains, red or red-streaked kernels, damaged grains, foreign varieties, extraneous matter, paddy grains, contaminants and grain dimensions (EAC, 2011; KEBS, 2023). For Pishori, long-grain and slenderness expectations are important because the market value of aromatic rice depends strongly on intact long kernels and uniform appearance (KEBS, 2023).

Table 1. Rice quality standards and definitions used to interpret the image-analysis results.

Quality item	Relevant requirement or definition	Reference standard
Head rice	Kernel or part-kernel length $\geq 75\%$ of reference/test-sample average length	EAS milled rice and KEBS Pishori specification (EAC, 2011; KEBS, 2023)
Broken rice	Pieces shorter than three-quarters of the whole/reference kernel	EAS milled rice and KEBS Pishori specification (EAC, 2011; KEBS, 2023)
Pishori long grain	Average kernel length approximately 6.00-6.99 mm; extra-long ≥ 7.00 mm	KEBS DKS 2087:2023 public-review draft (KEBS, 2023)
Pishori slender shape	Kernel length more than three times breadth (aspect ratio > 3)	KEBS DKS 2087:2023 public-review draft (KEBS, 2023)
Moisture	Pishori paddy/brown rice for milling: not more than about 14%; generic milled rice moisture limits commonly near 13-14%	KEBS DKS 2087:2023 and EAS 128:2011 (EAC, 2011; KEBS, 2023)
Broken-rice grade limits	Pishori draft: Premium 5%, Grade 1 15%, Grade 2 25%, Grade 3 35% by mass; generic EAS milled rice: Grade 1 5%, Grade 2 7%, Grade 3 15%	KEBS DKS 2087:2023 and EAS 128:2011 (EAC, 2011; KEBS, 2023)
Colour and defects	Uniform colour, desirable appearance; limits for chalky/green immature, red/red streaked and damaged grains	KEBS DKS 2087:2023 and EAS 128:2011 (EAC, 2011; KEBS, 2023)

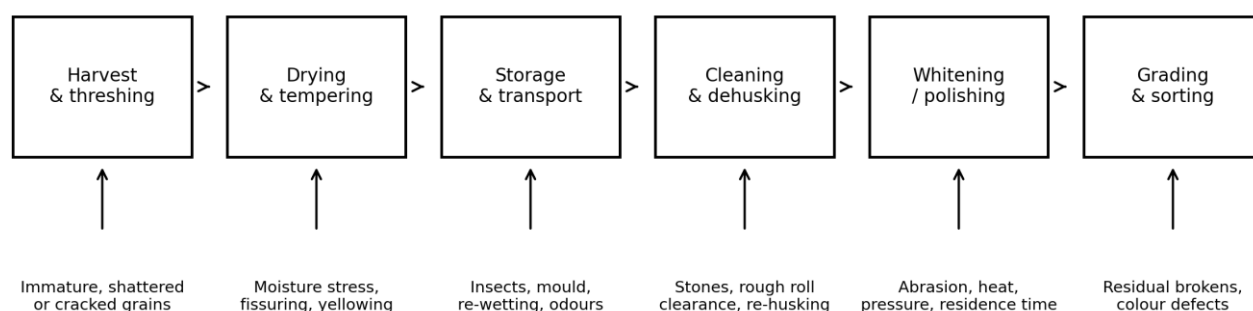
1.3 Literature review: quality-sensitive points in post-harvest and milling

Post-harvest handling affects rice quality through mechanical damage, moisture stress, biological deterioration and contamination. FAO guidance states that newly harvested high-moisture paddy should be dried promptly and milled when dry, commonly around 14% moisture content, because wet soft grain may powder during milling and very dry brittle grain may produce excessive broken (FAO, n.d.). IRRI similarly emphasizes that paddy moisture content and purity strongly influence milling quality and that very low moisture content increases grain breakage and reduces head rice recovery (IRRI, n.d.-c).

Milling quality is governed by paddy condition, machine type, degree of milling, operator settings and the ability of the mill to remove husk and bran without excessive endosperm loss. Proper rice milling ideally separates husk, bran, germ and milled rice fractions while preserving the whole kernel; however, real milling recovery is affected by variety, crop history and equipment type (IRRI, n.d.-b; IRRI, n.d.-d). In abrasive whitening, frictional and compressive stresses are unavoidable, making feed rate, pressure, residence time, aspiration and grading important control variables for long-grain rice.

Image analysis is increasingly used for objective rice-quality assessment because it can measure kernel length, breadth and aspect ratio at a much larger scale than manual inspection. Recent image-processing and machine-vision studies demonstrate the suitability of digital measurements for grain-size measurement, defect classification and kernel-quality estimation (Tyagi et al., 2025; Wang et al., 2022). In this study, image-analysis was used to quantify dimensional changes from brown rice through whitening and final grading.

Critical control points affecting aromatic long-grain rice quality



Quality outcomes: head rice yield, broken percentage, whiteness, chalkiness, discoloration, purity, aroma and market grade.

Figure 2. Critical control points where post-harvest handling and milling can affect broken rice, colour defects and market grade.

2. Materials and methods

2.1 Study material and data source

The study used image-analysis dimensional measurements of aromatic long-grain rice variety Pishori obtained from Mwea Rice Millers Ltd. The samples represented three processing stages: brown rice, white rice before grading and white rice after grading. Brown rice represents rice after dehusking, white rice before grading represents the product after whitening/polishing but before final length grading, and white rice after grading represents the final graded head-rice outlet.

Table 2. Data sources and image-analysis variables used in the study.

Processing stage	Valid kernels (n)	Variables
Brown rice	2199	Length_mm, Breadth_mm, Aspect_Ratio
White rice before grading	2899	Length (mm), Breadth (mm), Aspect Ratio
White rice after grading	2767	Length (mm), Breadth (mm), Aspect Ratio

2.2 Image-analysis variables

Each row represented one kernel or kernel fragment detected by image analysis (Table 1). The available variables were kernel length (mm), breadth (mm) and aspect ratio. Aspect ratio was treated as length divided by breadth and was used to interpret slenderness. The attached files did not contain raw images, pixel calibration details, kernel mass, moisture, whiteness, chalkiness, fissuring scores or colour coordinates. Therefore, statistical analysis focused on dimensional quality, especially broken rice. Colour and discolouration defects were interpreted from standards and literature but were not quantified from the provided data.

Table 1: Sample data extracted from a rice sample image

Length (mm)	Breadth (mm)	Aspect Ratio
6.74	2.11	3.19
6.61	1.85	3.58
3.56	1.98	1.8
3.18	1.85	1.72
4.83	1.98	2.44
3.94	1.72	2.3
5.34	1.72	3.11
6.48	1.98	3.27
8.26	2.38	3.48
3.43	2.11	1.62
6.61	1.45	4.55
4.45	1.85	2.41
3.05	1.98	1.54
6.86	1.98	3.47
3.43	2.11	1.62
3.18	1.45	2.19
2.54	1.32	1.93
3.56	1.98	1.8
1.27	0.92	1.38
3.3	1.98	1.67

2.3 Data cleaning and classification

Blank and non-numeric records were excluded. The final dataset contained 7,865 valid kernel observations. Following Pishori dimensional requirements, whole-looking reference kernels were defined as kernels with length ≥ 6.0 mm and aspect ratio ≥ 3.0 , reflecting long and slender grain expectations for Pishori interpretation (KEBS, 2023).

The mean length of these reference kernels across the combined dataset was used as the reference whole-kernel length. The resulting reference length was 6.812 mm. The head-rice threshold was $0.75 \times 6.812 = 5.109$ mm; the large-broken and medium-broken boundaries were 3.406 mm and 1.703 mm, respectively. Kernels were classified as follows: head rice equivalent, length $\geq 0.75 \times$ reference length; large broken, $0.50\text{--}0.75 \times$ reference length; medium broken, $0.25\text{--}0.50 \times$ reference length; and small broken/chips, $<0.25 \times$ reference length, consistent with standards-based use of the three-quarters reference-length criterion for head rice and broken kernels (EAC, 2011; KEBS, 2023). Whole-grain percentage was also reported separately using length ≥ 6.0 mm. The official standards use mass percentages, while the present image-analysis output gives count percentages; therefore, grade comparisons are indicative rather than official certification (EAC, 2011; KEBS, 2023).

2.4 Statistical analysis

Descriptive statistics were computed for kernel length, breadth and aspect ratio at each processing stage. One-way analysis of variance (ANOVA) was used to test whether stage means differed significantly. Because kernel dimensions can be skewed and sample sizes were large, the non-parametric Kruskal-Wallis test was also used as a robustness check. Welch pairwise t-tests with Bonferroni adjustment were used to compare stages. A chi-square test of independence was applied to test whether the head-rice/broken-rice composition differed by stage. Effect size was reported as eta-squared for ANOVA and Cramer's V for chi-square tests.

3. Results and discussion

3.1 Descriptive dimensional characteristics

The brown rice sample had a mean length of 5.980 mm, a median length of 6.740 mm and a whole-grain share of 68.94%, indicating that many kernels were intact but a substantial broken fraction was already present before whitening. The mean length then decreased to 5.098 mm before grading and increased to 5.568 mm after grading. This pattern is consistent with a milling line in which whitening produces additional fragments and grading removes part of the shorter broken fraction, thereby improving the average length of the final head-rice stream. (IRRI, n.d.-b; IRRI, n.d.-d).

Table 3. Descriptive statistics for kernel dimensions measured by image analysis.

Stage	Variable	n	Mean	SD	Min	Q1	Median	Q3	Max	CV (%)
Brown rice	Length (mm)	2,199	5.980	1.686	1.14	4.58	6.74	7.12	8.39	28.2
Brown rice	Breadth (mm)	2,199	1.942	0.274	0.13	1.85	1.98	2.11	3.43	14.1
Brown rice	Aspect ratio	2,199	3.086	0.945	1.10	2.44	3.31	3.66	24.07	30.6
White rice before grading	Length (mm)	2,899	5.098	1.763	1.40	3.43	5.97	6.61	11.31	34.6
White rice before grading	Breadth (mm)	2,899	1.912	0.249	0.79	1.72	1.98	2.11	2.90	13.0
White rice before grading	Aspect ratio	2,899	2.648	0.847	1.04	1.81	2.89	3.37	5.71	32.0
White rice after grading	Length (mm)	2,767	5.568	1.501	1.91	4.07	6.23	6.74	7.88	27.0
White rice after grading	Breadth (mm)	2,767	1.947	0.209	1.19	1.85	1.98	2.11	3.04	10.7
White rice after grading	Aspect ratio	2,767	2.866	0.760	1.11	2.13	3.12	3.44	5.39	26.5

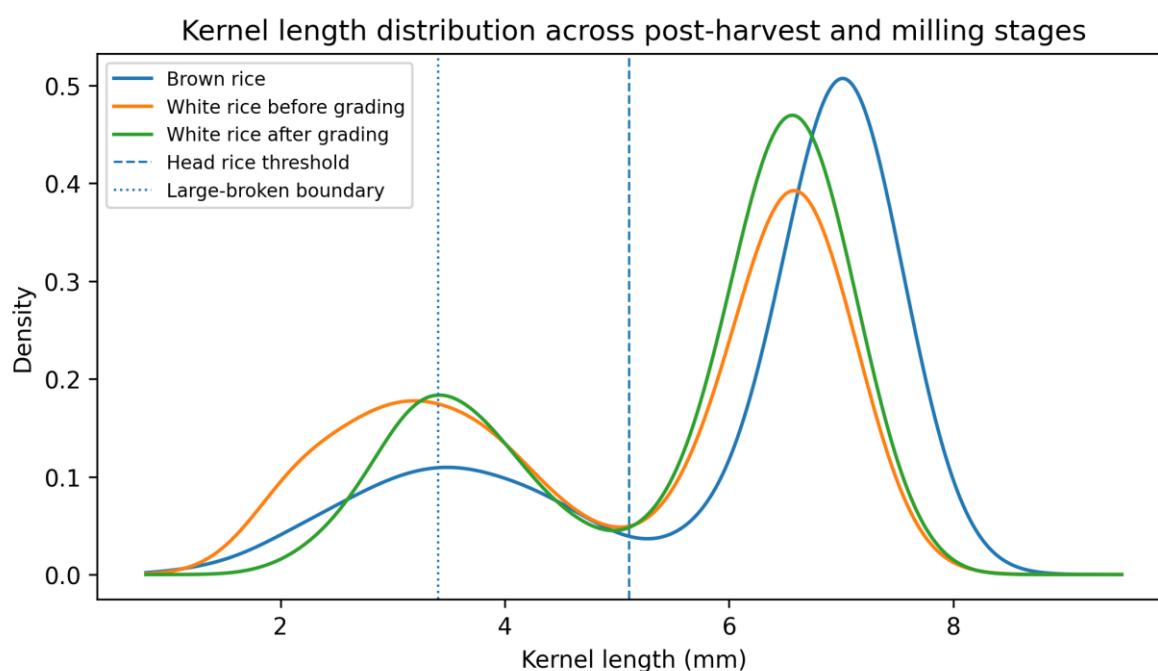


Figure 3. Kernel length distributions showing the shift toward smaller fragments after whitening and partial recovery after grading.

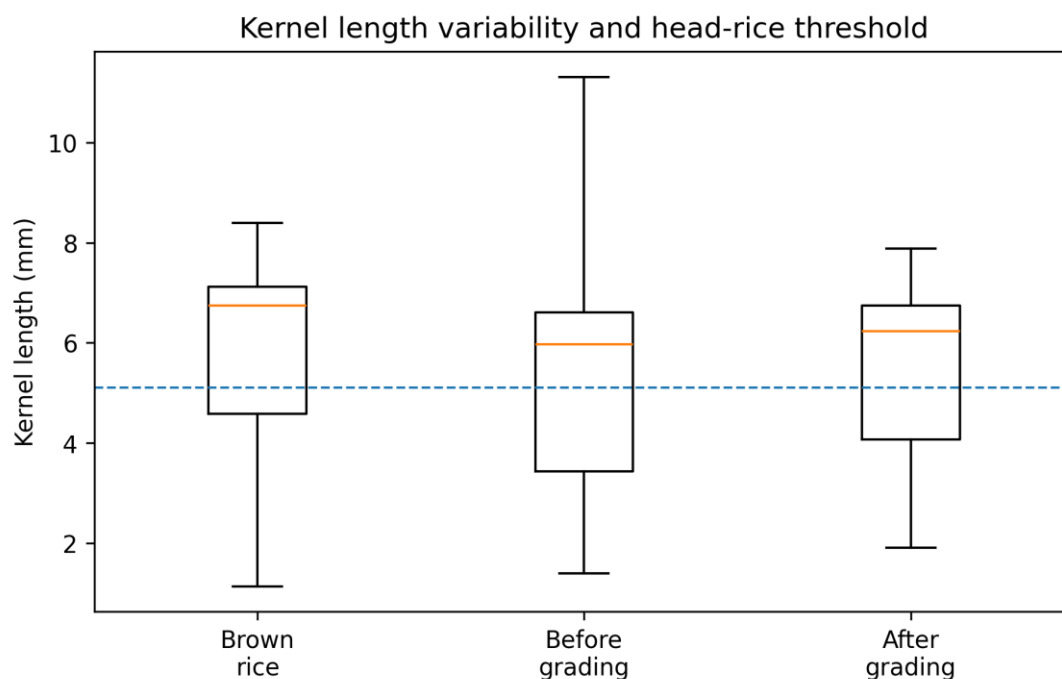


Figure 4. Kernel length variability by processing stage; dashed line indicates the calculated head-rice threshold.

3.2 Head rice and broken rice classification

The calculated head-rice equivalent was 72.44% in brown rice, 56.61% before grading and 67.76% after grading. Conversely, broken rice increased from 27.56% in brown rice to 43.39% before grading, confirming that whitening is the dominant breakage stage in the measured process. The interpretation follows the standards-based definition of broken rice as kernels or pieces shorter than three-quarters of the reference whole kernel (EAC, 2011; KEBS, 2023).

Table 4. Kernel class distribution based on reference-length thresholds.

Stage	Kernel class	Count	Count percentage (%)
Brown rice	Whole grains ($L \geq 6.0$ mm)	1,516	68.94
Brown rice	Head rice equivalent ($L \geq 0.75 \times$ reference length)	1,593	72.44
Brown rice	Broken rice ($<0.75 \times$ reference length)	606	27.56
Brown rice	Large broken ($0.50\text{-}0.75 \times$ reference length)	329	14.96
Brown rice	Medium broken ($0.25\text{-}0.50 \times$ reference length)	264	12.01
Brown rice	Small broken/chips ($<0.25 \times$ reference length)	13	0.59
White rice before grading	Whole grains ($L \geq 6.0$ mm)	1,407	48.53
White rice before grading	Head rice equivalent ($L \geq 0.75 \times$ reference length)	1,641	56.61
White rice before grading	Broken rice ($<0.75 \times$ reference length)	1,258	43.39
White rice before grading	Large broken ($0.50\text{-}0.75 \times$ reference length)	539	18.59

Stage	Kernel class	Count	Count percentage (%)
White rice before grading	Medium broken (0.25-0.50 x reference length)	706	24.35
White rice before grading	Small broken/chips (<0.25 x reference length)	13	0.45
White rice after grading	Whole grains ($L \geq 6.0$ mm)	1,593	57.57
White rice after grading	Head rice equivalent ($L \geq 0.75$ x reference length)	1,875	67.76
White rice after grading	Broken rice (<0.75 x reference length)	892	32.24
White rice after grading	Large broken (0.50-0.75 x reference length)	516	18.65
White rice after grading	Medium broken (0.25-0.50 x reference length)	376	13.59
White rice after grading	Small broken/chips (<0.25 x reference length)	0	0.00

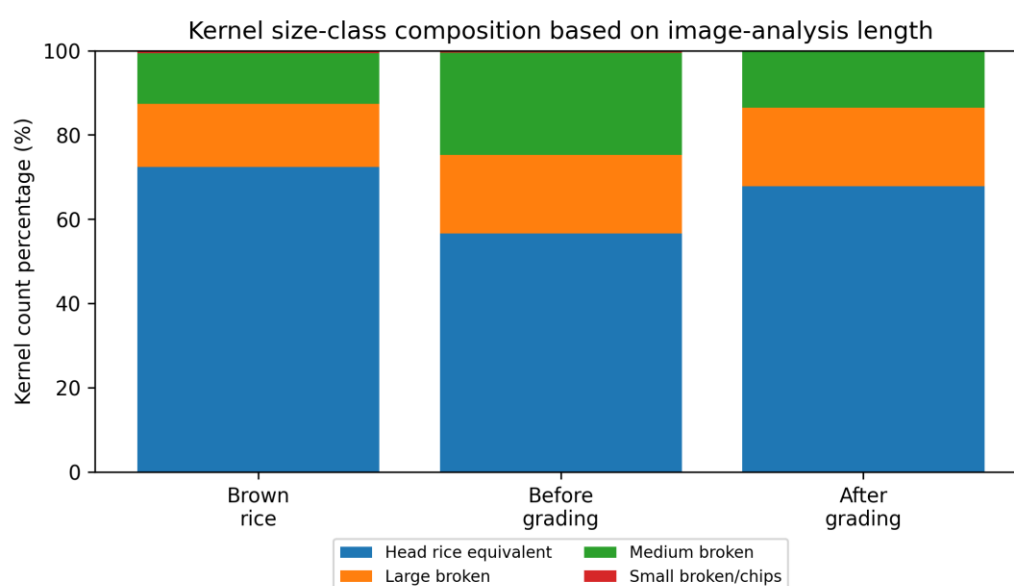


Figure 5. Percentage composition of head rice equivalent, large broken, medium broken and small broken/chips across processing stages.

The fact that brown rice already contained 27.56% broken kernels indicates that the quality problem did not begin only at whitening. Critical upstream contributors may include delayed harvest, rough threshing, uneven drying, re-wetting, brittle kernels at low moisture content, rough transport and repeated handling. These mechanisms are consistent with post-harvest literature showing that paddy moisture, drying conditions, handling and paddy quality strongly influence subsequent milling recovery and head rice yield (FAO, n.d.; IRRI, n.d.-c; IRRI, n.d.-d).

3.3 Aspect ratio and slenderness changes

Pishori is expected to be long and slender, and the Pishori specification places emphasis on grain length and slender shape as market-quality attributes (KEBS, 2023). The mean aspect

ratio declined from 3.086 in brown rice to 2.648 before grading, then improved to 2.866 after grading. This change is consistent with the removal of some shorter and wider fragments during grading, although the final rice still contained many kernels below the slenderness expectation.

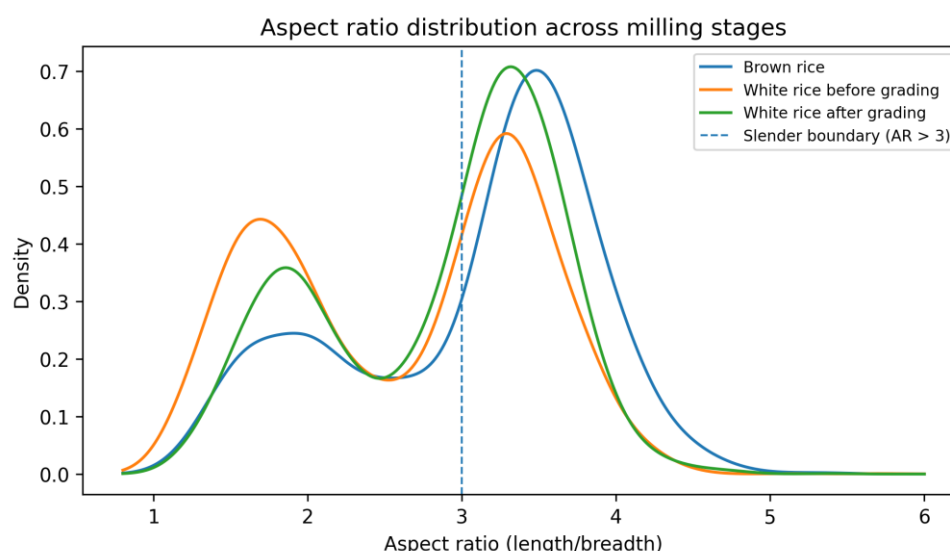


Figure 6. Aspect ratio distributions showing reduction in slenderness after whitening and partial improvement after grading.

3.4 Inferential statistics

The statistical tests confirmed significant dimensional changes across the process stages. ANOVA showed significant stage effects for length, breadth and aspect ratio, and Kruskal-Wallis tests gave the same conclusion. The largest practical effects were observed for length and aspect ratio, which are the main dimensional indicators of breakage and slenderness. The chi-square test also showed a significant association between processing stage and head-rice/broken-rice composition.

Table 5. Inferential statistical tests for dimensional variables and kernel-class composition.

Response / composition	ANOVA F or Chi-square	p-value	Kruskal H / df	p-value / effect size	Eta-squared
Length (mm)	180.607	2.05e-77	586.722	3.93e-128	0.0439
Breadth (mm)	17.203	3.51e-08	38.557	4.24e-09	0.0044
Aspect ratio	168.658	1.91e-72	367.895	1.30e-80	0.0411
Head rice vs broken composition	Chi-square = 152.520	7.60e-34	df = 2	Cramer V = 0.139	
Four-class kernel composition	Chi-square = 222.780	2.66e-45	df = 6	Cramer V = 0.119	

Table 6. Pairwise stage comparisons for kernel dimensions.

Variable	Stage A	Stage B	Mean difference A-B	Welch t	Bonferroni p
Length (mm)	Brown rice	White rice before grading	0.882	18.140	1.01e-70
Length (mm)	Brown rice	White rice after grading	0.412	8.985	1.13e-18
Length (mm)	White rice before grading	White rice after grading	-0.470	-10.814	1.65e-26
Breadth (mm)	Brown rice	White rice before grading	0.030	4.081	1.37e-04
Breadth (mm)	Brown rice	White rice after grading	-0.005	-0.694	1.00e+00
Breadth (mm)	White rice before grading	White rice after grading	-0.035	-5.785	2.30e-08
Aspect ratio	Brown rice	White rice before grading	0.439	17.153	1.98e-63
Aspect ratio	Brown rice	White rice after grading	0.220	8.883	2.84e-18
Aspect ratio	White rice before grading	White rice after grading	-0.218	-10.218	8.05e-24

3.5 Critical quality areas identified from data and literature

The dimensional evidence and literature jointly identify five high-priority areas in the Pishori value chain. First, harvest and threshing are critical because immature kernels, shattering and impact damage can initiate cracks before milling. Second, drying and tempering are critical because moisture gradients and over-drying promote fissuring. Third, storage and transport are critical because moisture uptake, pest damage and rough bag handling can create discoloured or weakened kernels. Fourth, husking and paddy separation are critical because repeated husking and poor roll adjustment can damage brown rice. Fifth, whitening and grading are critical because abrasive stress creates most new fragments, while grading determines how much broken rice remains in the final product. These control points agree with FAO and IRRI guidance on the role of paddy moisture, drying, milling equipment and operator control in determining milling recovery and rice quality (FAO, n.d.; IRRI, n.d.-a; IRRI, n.d.-c; IRRI, n.d.-d).

Table 7. Critical areas where Pishori post-harvest and milling quality is greatly affected.

Critical area	Main mechanism	Quality defect caused	Recommended control
Harvest timing	Immature grains if early; shattering, field cracks and weather damage if late	Chalkiness, cracks, broken kernels, lower head rice yield	Harvest at optimum maturity and avoid field exposure after maturity

Critical area	Main mechanism	Quality defect caused	Recommended control
Threshing	Excessive drum speed, rough impact and overfeeding	Hidden cracks that break during husking/whitening	Correct threshing speed, avoid repeated threshing and minimise impact surfaces
Drying and tempering	Delayed drying, rapid drying, over-drying, re-wetting and non-uniform moisture	Fissuring, yellowing, mould, lower head rice yield	Dry promptly to safe moisture, use moisture meters, avoid re-wetting and provide tempering time
Storage and transport	Moisture uptake, insects, rodents, fungi, bag dropping and contamination	Discoloured, mouldy, insect-marked, off-odour or contaminated rice	Cool dry storage, aeration, pest control, clean bags, palletisation and gentle handling
Cleaning before milling	Stones, sand, straw, immature grains and foreign matter	Machine wear, contamination, uneven milling and breakage	Use pre-cleaners, de-stoners, magnets and aspiration before husking
Husking/dehusking	Incorrect rubber roll clearance, pressure or roll speed; worn rollers	Broken brown rice and cracked kernels	Regular adjustment, roller replacement and controlled feed rate
Paddy separation	Re-husking already dehulled brown rice	Additional breakage and paddy contamination in the whitener	Efficient paddy separators and return only unhulled grains to husker
Whitening/polishing	High pressure, long residence time, abrasive stone wear, insufficient air flow and heat	Major increase in broken rice, excessive bran removal, surface scratches and whiteness defects	Optimise feed, pressure, chamber resistance, air flow, degree of milling and temperature
Grading and colour sorting	Incorrect sieve/indented-cylinder settings, overloading or weak colour sorting	Residual broken, chalky/discoloured grains and lower market grade	Maintain length graders, adjust loads, monitor rejects and calibrate colour sorter
Final packaging/storage	Moisture ingress, odour absorption, insects and poor sealing	Loss of whiteness, aroma deterioration, mould and infestation	Food-grade packaging, sealing, dry storage, pest monitoring and first-in-first-out stock rotation

3.6 Interpretation against Pishori market quality

Although official rice grades are based on mass percentage rather than kernel-count percentage, the image-analysis results clearly indicate where grade loss occurs. The white rice after grading still contained 32.24% broken kernels by count, showing that grading improved but did not fully correct the damage created earlier. Therefore, dimensional image analysis should be interpreted as a diagnostic tool for locating breakage points, while final commercial grading should be complemented with mass-based grading and defect assessment in line with milled-rice standards (EAC, 2011; KEBS, 2023).

4. Conclusions

The study used image-analysis dimensional measurements to identify critical quality-loss areas in aromatic long-grain Pishori rice during post-harvest handling and milling. The most important quantitative finding was that broken kernels increased from 27.56% in brown rice

to 43.39% in white rice before grading, showing that whitening/polishing was the most severe measured quality-loss stage. Grading reduced the broken fraction to 32.24%, demonstrating partial but incomplete recovery of head-rice concentration. Mean kernel length decreased from 5.980 mm in brown rice to 5.098 mm before grading and increased to 5.568 mm after grading. Aspect ratio followed a similar pattern, declining after whitening and partially improving after grading. Statistical tests confirmed significant differences among stages for length, breadth, aspect ratio and head-rice/broken-rice composition.

The findings demonstrate that Pishori quality is affected by a chain of interdependent critical control points rather than by a single milling operation. The key areas requiring control are harvest timing, threshing, drying, tempering, storage, transport, cleaning, husking, paddy separation, whitening, polishing, grading, colour sorting and final packaging. The most important interventions are moisture control, prevention of fissuring, gentle handling, adequate paddy cleaning, correct husker and whitener settings, efficient air flow and heat control during whitening, proper length-grader adjustment, and routine image-based monitoring of kernel dimensions.

Future work should combine dimensional image analysis with mass-based grading, moisture measurement, fissure detection, whiteness/chalkiness measurement, colour-space analysis and machine operating parameters. This would allow direct modelling of how drying conditions, feed rate, abrasive load, residence time and grader settings affect head rice yield, discolouration and market grade in Mwea Pishori rice.

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A GIS-Assisted Hydraulic Methodology for PAT-Based Energy Recovery from Existing Rural Gravity Water Schemes in Highland East Africa

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Abstract

Gravity-fed water systems in East African highlands continuously dissipate hydraulic energy at Pressure Reducing Valves (PRVs). A Pump-as-Turbine (PAT) can capture this energy, but current research lacks a framework to scale PATs across these networks. This paper presents a nine-step hydraulic protocol, validated against the Dabis micro-hydro reference site in Ethiopia ($H_{\text{gross}} = 17 \text{ m}$; $Q = 0.025 \text{ m}^3/\text{s}$) with a 4.6% head deviation from CFD simulations. The viability of these systems depends more on economic design than hydraulic constraints. A 1.96 kW PAT installation costs USD 1,500 to 2,800, compared to USD 20,000 for a conventional micro-hydro turbine. Under a standard household-only billing model, the system requires a 25-year payback. By adopting a productive-use tariff of USD 0.16/kWh (half the Kenyan national grid cost), the payback period drops to

4.3 years with a Levelized Cost of Energy (LCOE) of USD 0.032/kWh. A GIS-based regional screening identifies 190 kW to 1.35 MW of deployable capacity across Kenya, demonstrating that PAT technology delivers low-cost rural electrification when paired with demand-side load planning.

Keywords: Pump-as-Turbine, micro-hydro, pressure reducing valve, gravity water scheme, GIS site screening, East Africa, rural electrification, energy recovery.

1. Introduction

Africa holds about 12% of the world's hydropower potential but operates only 5% of its small hydropower capacity (Zhang, Adu, Suoming, & Koranteng, 2019). More than 600 million Africans lack modern electricity, with rural access remaining below 31% (World Bank, 2023). Extending the national grid to mountain communities' costs USD 15,000 to 25,000 per kilometer in rough terrain.

Many highland villages already operate gravity-fed water supply systems. These pipes carry water hundreds of meters from mountain rivers. When the water reaches a lower elevation, a Pressure Reducing Valve (PRV) drops the pressure to protect the distribution pipes. This process dissipates the hydraulic energy as heat and noise.

Running water backward through a standard centrifugal pump turns it into a turbine. This Pump-as-Turbine (PAT) configuration costs between USD 200 and 2,000, compared to USD 5,000 to 50,000 for a custom micro-turbine. The pumps are available in local markets and rely on standard mechanical parts (El-Deen, Ezzat, & Ali, 2024).

While researchers study PATs globally, a 2026 review of 918 micro-hydro papers found few applications in Africa (Duah, Sekyere, Kemausuor, & Amaning, 2026). Practitioners lack a standard method to calculate recoverable energy from existing water networks. Furthermore, Kenya's water regulator (WASREB) does not require utilities to track energy lost at PRVs. Thousands of valves dissipate pressure unmonitored.

This paper evaluates PAT viability through three components:

- 1) A nine-step engineering guide for recovering PAT energy from existing gravity water pipes, validated against the Dabis site in Ethiopia (4.6% accuracy).
- 2) An economic framework showing that a "sell at half" productive-use tariff yields a 4.3-year payback and outperforms the national grid.
- 3) A GIS mapping framework indicating this model can scale across existing Kenyan PRV sites.

2. Literature Review

PAT Technology: Global State of Knowledge

Engineers have operated pumps in reverse since the 1930s, formalizing the design rules in the 1990s. Chapallaz, Eichenberger, and Fischer (1992) demonstrated that centrifugal pumps suit the 10 to 150 meter head range typical of East African water schemes (Dribssa, Nigussie, & Tsegaye, 2015).

Predicting a PAT's Best Efficiency Point (BEP) without manufacturer data remains the primary technical challenge. Derakhshan and Nourbakhsh (2008) tested centrifugal pumps and developed formulas to predict turbine performance from standard pump data (Derakhshan & Nourbakhsh, 2008). An older method by Stepanoff (1957) uses fixed ratios. Dribssa, Nigussie, and Tsegaye (2015) found that the Stepanoff method aligned with their computer simulations at the Ethiopian Dabis site (Dribssa et al., 2015).

Singh and Nestmann (2010) recommended using multiple prediction formulas simultaneously to improve selection accuracy (Singh & Nestmann, 2010). Hossain et al. (2023) compared multiple predictive methods, detailing their respective limitations (Hossain et al., 2023).

Alwan (2025) calculated that replacing PRVs with PATs in municipal water networks generates a net return (Alwan, 2025). Morabito and Hendrick (2019) extended this to smart water grids (Morabito & Hendrick, 2019). Castro et al. (2023) developed the mathematical background for integrating GIS and hydraulic modeling to identify energy recovery locations (Castro et al., 2023).

PAT in Africa: Identified Gaps

Few projects exist in rural Africa. Zhang et al. (2019) identified low capital cost as the primary advantage for African deployments, but noted a lack of site identification methods (Zhang et al., 2019). El-Deen et al. (2024) showed that standard radial-flow pumps achieve 55% to 75% efficiency, offering an alternative to Pelton turbines for 10 to 60 meter drops (El-Deen et al., 2024).

A 2026 review by Duah et al. found no published studies using GIS mapping to locate PRV energy sites in East Africa (Duah et al., 2026).

The Dabis site in Ethiopia provides the only peer-reviewed PAT data in highland East Africa with computational fluid dynamics (CFD) validation (Dribssa et al., 2015). That study focused on fluid dynamics rather than civil engineering; it used secondary data and omitted the pipe length and layout. The 100-meter pipe estimate in Section 5.1 is our derived calculation. Dribssa et al. used the Standard $k-\epsilon$ fluid model, which a 2025 review by Sun et al. notes can struggle with turbine blades, suggesting the SST $k-\omega$ model performs better (Sun et al., 2025). Consequently, our 4.6% deviation from the Dabis results approaches the likely error margin of their computer model.

For electrical control, Praptodiyono et al. (2021) demonstrated that starting a 300 W appliance without an Electronic Load Controller (ELC) crashes the generator voltage (Praptodiyono, Maghfiroh, Nizam, Hermanu, & Wibowo, 2021). They designed an ELC using variable phase-angle control to stabilize power output, a design we adopt here.

GIS-Based Screening: Methodological Precedents

Researchers have used SRTM 30 m satellite elevation data to map hydropower potential in Africa. The satellite data carries a 6 to 10 meter vertical error in mountainous terrain, making it suitable for initial prospecting rather than final design. We adapted the method from Castro et al. (2023) (Castro et al., 2023) for rural distribution lines.

We sourced pipe locations from WASREB water records. Chelelgo (2016) used similar software to locate natural river hydropower in Baringo County, Kenya (Chelelgo, 2016). While Chelelgo screened for new run-of-river sites, we target existing pipes using GPS coordinates from WASREB Impact Reports (WASREB, 2023).

3. Technical Background

Hydraulic Energy in Pressurized Systems

The total hydraulic head at any pipe cross-section is described by the Bernoulli equation:

$$H_{\text{total}} = z + \frac{P}{\rho g} + \frac{V^2}{2g}$$

Where z is elevation head (m), P is gauge pressure (Pa), ρ is water density (1000 kg/m^3), g is gravitational acceleration (9.81 m/s^2), and V is flow velocity (m/s). The elevation difference between a high intake and a low PRV dictates the dissipated energy:

$$P_{\text{wasted}} = \rho g Q \Delta H_{\text{PRV}} \quad [\text{Watts}]$$

PAT Operating Principle and Advantages

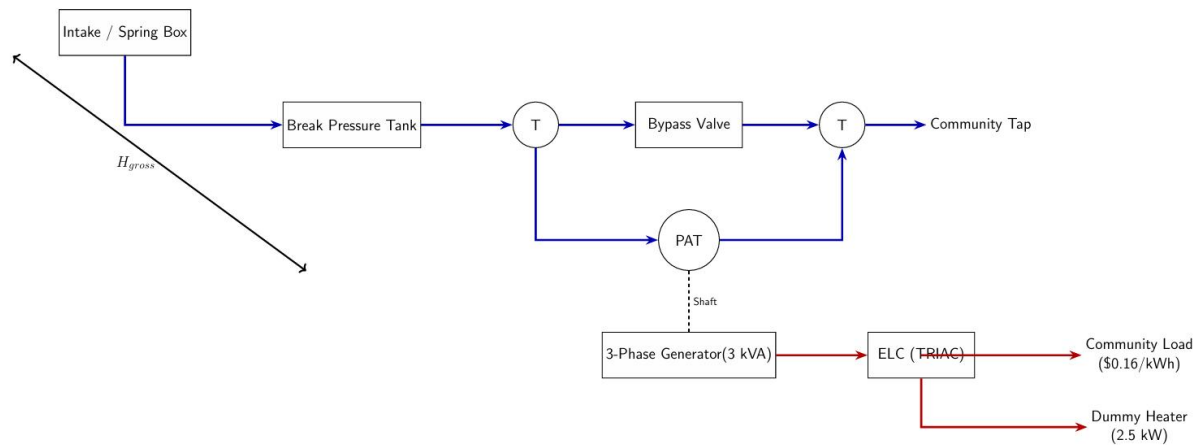


Figure 1: Schematic layout of the PAT energy recovery system, illustrating the bypass valve, electronic load controller, and rural distribution lines.

Running water into the discharge port of a centrifugal pump spins the impeller to drive a generator. Hydraulic behaviour is governed by the affinity laws:

$$Q \propto N \quad H \propto N^2 \quad P \propto N^3$$

The Best Efficiency Point (BEP) in turbine mode shifts to a higher head and flow compared to pump mode. Derakhshan and Nourbakhsh (2008) established these predictive formulas (Derakhshan & Nourbakhsh, 2008):

$$\frac{Q_{\text{PAT}}}{Q_{\text{pump_BEP}}} = 1.2N_s^{0.55}$$

$$\frac{H_{\text{PAT}}}{H_{\text{pump_BEP}}} = 1.2N_s^{0.55}$$

Where N_s is the dimensionless specific speed of the pump. This allows engineers to select a pump without proprietary turbine curves.

Electrical Power Output

$$P_{\text{electrical}} = \eta_{\text{PAT}} \eta_{\text{gen}} \rho g Q H_{\text{net}} \quad [\text{Watts}]$$

Typical values: $\eta_{\text{PAT}} = 0.55$ to 0.75 ; η_{gen} (induction) = 0.85 to 0.92 . An Electronic Load Controller (ELC) maintains a steady 50 Hz frequency by dumping excess power into a resistive ballast load, such as a water heater, using a TRIAC control system (Praptodiyono et al., 2021).

4. Methodology

Nine-Step Hydraulic Site Assessment Protocol

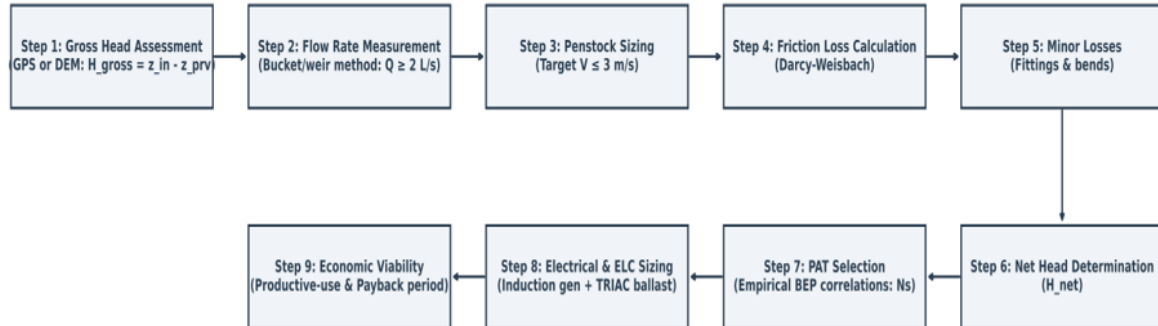


Figure 2: Nine-step PAT hydraulic assessment protocol flowchart.

This protocol relies on standard field equipment: a GPS receiver and basic flow measurement tools.

Step 1. Gross Head: Record GPS elevations at the intake and the PRV location. Compute:

$$H_{\text{gross}} = z_{\text{intake}} - z_{\text{PRV}} \quad [\text{m}]$$

Step 2. Flow Rate: Check the water committee records or measure the flow directly. We need a minimum of 2 L/s.

Step 3. Penstock Diameter: Select a diameter D to keep the water velocity V under 3 m/s:

$$D = \sqrt{\frac{4Q}{\pi V_{\text{design}}}} \quad [\text{m}]$$

Step 4. Friction Head Loss (Darcy-Weisbach):

$$h_f = f \frac{L}{D} \frac{V^2}{2g} \quad [\text{m}]$$

Friction factor f from the Moody chart. For PVC/HDPE smooth pipe, $f = 0.015$ to 0.018 .

Step 5. Minor Losses: Add 10% of the pipe friction to account for bends and valves:

$$h_{\text{minor}} = 0.10 \times h_f \quad [\text{m}]$$

Step 6. Net Head:

$$H_{\text{net}} = H_{\text{gross}} - h_f - h_{\text{minor}} \quad [\text{m}]$$

We require a minimum net head of 15 m.

Step 7. Water Hammer Check (Joukowsky):

$$\Delta P = \rho c \Delta V \quad [\text{Pa}]$$

Wave celerity c in PVC pipe is about 300 to 500 m/s. Valve closure must occur slowly enough to limit surge pressure to 2 bar above static.

Step 8. PAT Selection: Compute specific speed:

$$N_s = N \frac{Q^{0.5}}{H_{\text{net}}^{0.75}}$$

Apply the Derakhshan formula to find the right pump BEP.

Step 9. Electrical Output and Viability Screen:

$$\text{LCOE} = \frac{\text{CapEx} + \text{NPV}_{\text{O\&M}}}{E_{\text{lifetime}}} \quad [\text{USD/kWh}]$$

$$\text{Simple_Payback} = \frac{\text{CapEx}}{\text{Annual_Revenue} - \text{Annual_O\&M}}$$

We define a viable site as having a payback period under 5 years and an LCOE below USD 0.04/kWh.

GIS-Based Regional Screening Framework

This spatial tool identifies PRV sites across a county.

Inputs: SRTM 30 m DEM and WASREB Impact Reports.

Processing Steps (QGIS):

1. Download and clip the SRTM DEM to the target county.
2. Load the registered gravity scheme nodes (intake, break-pressure tanks, PRVs).
3. Extract the elevation at each node.
4. Calculate the drop between connected nodes.
5. Filter out any drops less than 15 m.
6. Estimate the pipe length. We multiply the straight-line distance by 1.4 to account for topographic routing. We then calculate Darcy-Weisbach losses to determine net head and power.

Validation Reference Site

We tested our method against the Dabis site in Ethiopia (Dribssa et al., 2015). Their published data: $H_{\text{gross}} = 17$ m, Design Flow = $0.025 \text{ m}^3/\text{s}$, and CFD BEP Head = 13.378 m.

5. Results and Discussions

Hydraulic Analysis – Dabis Validation Case

Applying the protocol: $H_{\text{gross}} = 17.0$ m. Selecting $D = 125$ mm yields $V = 2.04$ m/s.

Assuming $L \approx 6 \times H_{\text{gross}} = 100$ m, $h_f = 2.72$ m and $h_{\text{minor}} = 0.27$ m.

$$H_{\text{net}} = 17.0 - 2.72 - 0.27 = 14.0 \text{ m}$$

Our 14.0 m result deviates from the published 13.378 m CFD head by 4.6%. The specific speed $N_s = 32.8$ falls in the radial flow centrifugal pump range. The resulting electrical output is 1.96 kW. The 2.70 kW figure published by Dribssa et al. represents hydraulic power prior to generator losses.

Safety and Operational Checks

If the system loses electrical load and reaches runaway speed, closing the emergency valve in 3 seconds spikes the pressure to 14.09 bar. This exceeds the rating of a standard PVC Class 10 pipe (Lupa, Gagnon, Muntean, & Abdul-Nour, 2022). We specify a minimum 5-second closure time for the bypass valve to prevent fracture.

Electrical System Design & Village Load Matching

A typical 50-household village consumes 6.88 kWh daily. The PAT generates 47.1 kWh over the same period. The community utilizes only 14.6% of the generated power, leaving the ELC to dissipate the remaining 85.4% as heat.

The total capital expenditure (CapEx) for a 1.96 kW PAT installation, including the generator, ELC, and civil works, ranges from USD 1,500 to 2,800.

Model A (Household-only billing): Billing only metered household consumption at a baseline rate (USD 0.16/kWh) leaves the surplus power unmonetized. Due to low total utilization, this model still yields a 7.5-year payback period.

Model B (Water-Energy Nexus): The water committee redirects 30% of the surplus power into scheduled productive loads, such as maize milling or agro-processing. Pricing this power

at USD 0.16/kWh—half the Kenyan rural grid (KPLC) rate—reduces the payback period to 4.3 years and results in an LCOE of USD 0.032/kWh.

Cost Effectiveness Analysis

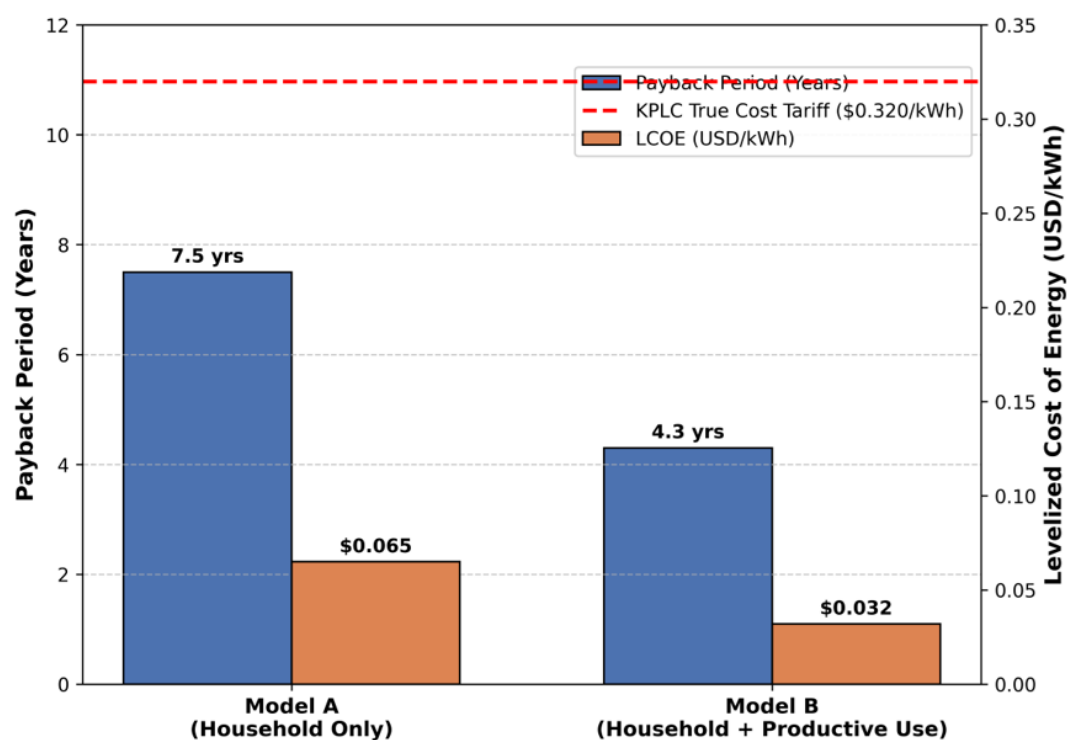


Figure 3: Cost effectiveness comparison highlighting the drop in payback period and LCOE under the productive-use Model B, compared against the KPLC grid tariff.

Table 1: Economic Comparison: PAT vs Conventional Alternatives

Energy Supply Option	Capacity	CapEx	LCOE	Tariff
Existing PAT (Opa River) (Adejumobi, Olatunji, & Oyelami, 2018)	50.0 kW	~\$2,500*	<\$0.05	N/A
Micro-Hydro (Francis) (Adejumobi et al., 2018)	50.0 kW	~\$20,000*	~\$0.15	N/A
Proposed PAT (Model B)	1.96 kW	\$1,500–2,800	\$0.032	\$0.160
KPLC Grid (Rural Kenya)	Grid	~\$270 (Fee)	N/A	\$0.320

* Cost reflects mechanical unit only, excluding civil works.

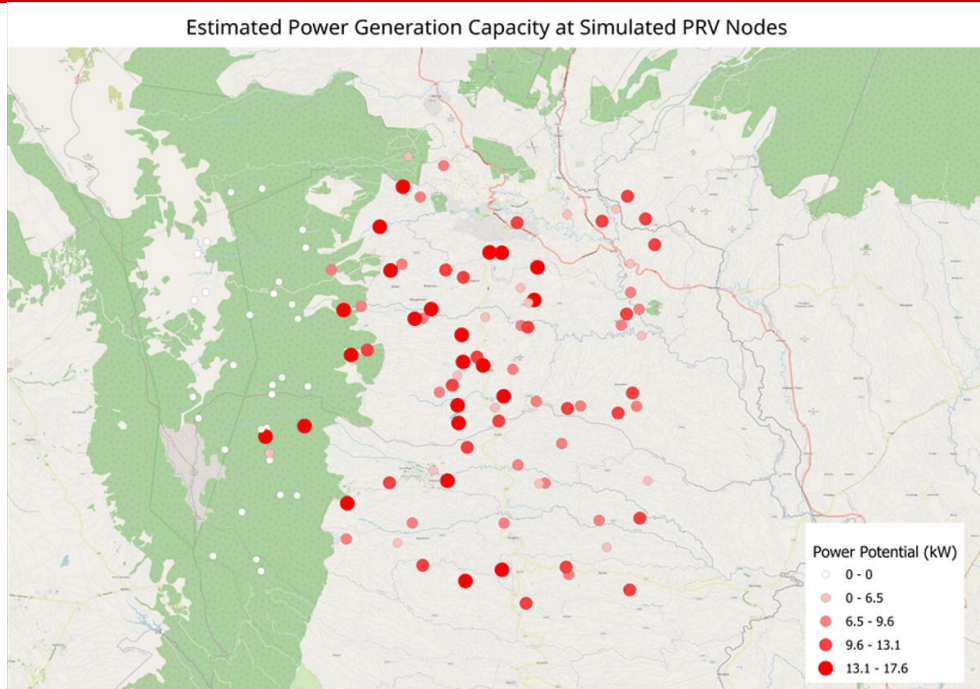


Figure 4: GIS map showing the estimated power generation capacity at simulated PRV nodes across the eastern Aberdare slopes.

Running the spatial filter over a 30-scheme synthetic network yielded 79 qualifying pipe segments out of 104, representing 181 kW of total capacity. Scaling this to Kenya's 2,800 registered water schemes suggests a theoretical potential of 1.0 to 6.8 MW. Assuming a 20% development rate due to financing and site access constraints, the deployable capacity ranges from 190 kW to 1.35 MW.

Sensitivity Analysis

A sensitivity analysis shows that the payback period depends heavily on the productive-use capture fraction rather than physical variations in penstock length (Table 2).

Table 2: Sensitivity Analysis of Key Parameters

Parameter	Base	Low Case	High Case	Power Range	Payback
η_{PAT}	0.65	0.55	0.75	1.66–1.91 kW	6.4–4.7 yr
Penstock Length L	100 m	60 m	200 m	2.00–1.87 kW	5.3–5.6 yr
Capture Fraction	30%	15%	50%	Constant	8.5–3.9 yr

Study Assumptions and Limitations

The analysis relies on the following constraints:

- **Data Privacy:** Because raw WASREB geodata is proprietary, the GIS screening uses a topologically realistic synthetic dataset of 30 schemes modeled on the eastern Aberdare slopes.
- **Hydraulic estimates:** We assume $\eta_{\text{PAT}} = 0.65$ and generator $\eta_{\text{gen}} = 0.88$. We estimate penstock length using a topographic contour multiplier of $6 \times H_{\text{gross}}$.
- **Material Properties:** The wave celerity calculations assume PVC/HDPE pipes ($c \approx 400$ m/s). Applying steel pipe formulas would incorrectly classify these systems as unsafe.
- **Topographic Error:** SRTM 30 m DEMs have a vertical root-mean-square error of ± 6 – 10 m in highland terrain. The GIS tool functions as a regional screening mechanism, not a replacement for site surveys.

6. Conclusion

Recovering energy from rural water infrastructure using PATs depends on demand planning. A 1.96 kW PAT system costs between USD 1,500 and 2,800 to install. Financial viability requires a productive-use billing model. Pricing the power at USD 0.16/kWh reduces the payback period to 4.3 years and achieves an LCOE of USD 0.032/kWh. Regional GIS mapping indicates up to 1.35 MW of deployable capacity in Kenya. PAT technology offers a low-cost method for rural electrification when paired with an economic model that monetizes surplus generation.

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Evaluating the Effectiveness of Partial Replacement of Cement Using Powdered Pumice on the Mechanical Properties of Recycled Aggregate Concrete

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Abstract

Sustainability in construction has become a priority, driving research into efficient raw material utilization and emission reduction. With the increasing shortage of landfill space and strict environmental regulations, recycled aggregates (RA) have emerged as a viable resource for sustainable concrete production. However, RA's high porosity and residual mortar weaken the Interfacial Transition Zone (ITZ), increasing cracking and reducing bond strength. This study investigated the effectiveness of partially replacing cement with powdered pumice to mitigate ITZ deficiencies and enhance the mechanical properties of recycled aggregate concrete (RAC). A 0.55 water-to-cement ratio was maintained across all mixes, with 50% of natural coarse aggregates replaced by RA. Cement was partially substituted with powdered pumice at levels of 10%, 20%, 30%, 40%, and 50% by weight. The physical and mechanical properties of RA, pumice, and the resulting concrete were evaluated and compared to conventional concrete. Results indicated that a 10% pumice replacement (M2) achieved the highest compressive strength of 32.57 MPa. The optimal replacement level was identified at 19.42%, which maintained compressive strength above 30 MPa while reducing cement use, enhancing ITZ performance, and improving bond strength and durability. Beyond 19.42%, compressive strength dropped below structural-grade thresholds due to pumice's low calcium oxide (CaO) content (0.15%), which limited pozzolanic activity and reduced cementitious compound formation. ITZ analysis confirmed improved particle packing and matrix cohesion at moderate pumice levels, while higher replacements (>30%) increased porosity, void formation, and early-age cracking. The findings demonstrate that pumice-modified RAC when optimally dosed, can reduce cement consumption by 19.42%, enhanced durability, and

production of lightweight concrete suitable for load-bearing applications hence offering a balance between environmental performance and structural integrity.

Keywords - Recycled Aggregate Concrete (RAC), Powdered Pumice, Interfacial Transition Zone (ITZ), Compressive Strength.

1. Introduction

The increasing global demand for construction aggregates projected to surpass 26.8 billion tonnes annually has prompted a shift toward more sustainable building practices (Haider et al., 2022). In Kenya, this demand is mirrored by rapid construction growth, yet 4 million tonnes of construction and demolition waste (CDW) are annually disposed of in landfills, causing significant environmental concerns (Haider et al., 2022). Recycled Aggregates (RA) present a sustainable alternative to natural aggregates by minimizing raw material extraction, lowering transportation costs, and reducing landfill waste (Marvila et al., 2022). Similarly, pumice, a lightweight volcanic rock rich in silica and alumina, is gaining attention as a low-energy, environmentally friendly binder (Karatas et al., 2019; Adesina, 2020). However, the high porosity and residual mortar of RA weaken the Interfacial Transition Zone (ITZ), leading to reduced bonding and increased cracking. Larger RA particles exacerbate these deficiencies by expanding the ITZ, compromising concrete strength. This study addresses these challenges by evaluating the incorporation of powdered pumice to improve ITZ performance and mechanical properties of recycled aggregate concrete (RAC). The research aligns with the UN's 2030 Sustainable Cities agenda by promoting resource-efficient materials and reducing urban environmental impacts through sustainable construction innovations.

2. Literature Review

Research shows that the size of EPS beads significantly impacts compressive strength, with smaller beads The literature affirms that Recycled Aggregate Concrete (RAC) can be a sustainable alternative to conventional concrete, though it presents mechanical and structural limitations. Optimal performance is achieved when 50% of natural aggregate is replaced with recycled aggregate (RA) at a water-cement ratio of 0.45, attaining compressive strengths of up to 52.33 MPa (Jagan et al., 2021). However, full substitution leads to strength reductions and diminishes properties such as ductility and toughness (Elsayed et al., 2023; Bravo-German et al., 2021). Despite these drawbacks, studies confirm that RAC can still meet structural

standards under certain conditions (Cantero et al., 2020; Akpinar & Al, 2021; Zhan et al., 2022).

Pumice, a pozzolanic material primarily composed of silica and alumina, has historically contributed to durable constructions such as Roman cement (Safari et al., 2020; Mesfun et al., 2019). Pumice improves concrete by reducing density, enhancing thermal insulation, and resisting chemical attack (Alqarni, 2022; ; Ramanathan et al., 2020). Although it lowers concrete strength compared to traditional aggregates, combining pumice with other materials can maintain structural integrity (Mehrabi et al., 2021).

Research gaps exist regarding the role of pumice as an alkali-activated binder (AAB) in improving the weak Interfacial Transition Zone (ITZ) in RAC. While prior studies highlight the pozzolanic benefits of pumice, little is known about its combined use with RA to mitigate issues like cracking, permeability, and ITZ weaknesses (Ahmad, 2020). This research aims to fill that gap by assessing how powdered pumice, used as a partial cement replacement, affects RAC's mechanical strength, durability, workability, and microstructure.

3. Methodology

3.1 Material Sources and Preparation

The raw materials employed were recycled aggregates (RA), pumice, fine aggregates, coarse aggregates, Portland pozzolana cement, calcium hydroxide, and water.

3.1.1 Recycled aggregates (RA)

Recycled aggregates from Nairobi demolition sites were crushed, cleaned, and screened, then blended with fresh concrete to produce recycled aggregate concrete. The Recycled aggregates, is as shown in Figure 3.1.



Figure 3.1: Disposed Demolitions and Recycled aggregates

3.1.2 Pumice

Pumice from Naivasha and Mt. Kenya regions was manually collected, crushed into powder using hammers or a ball mill, and sieved to 75 microns for use as partial cement replacement.



Figure 3.3: Pumice stones

3.2 Mix design

3.2.1 Mix specifications

This mix follows BRE and DOE methods, with a grade of 30MPa, OPC class 42.5, slump range of 60–180mm, coarse aggregate (2.67 SG, 75% passing 20mm sieve), and fine aggregate (2.40 SG, 65% passing 0.6mm sieve).

3.2.2 Determining the Target strength (f_m)

$$f_m = f_k + M \dots\dots\dots (3.1)$$

Where: f_k = the specified characteristic strength, M = The margin is given by $(k*s)$, k = Constant, and s = Standard deviation.

$$f_m = 25 + (2.5*1.96) = 29.9 \approx 30\text{MPa}.$$

Using Equation 3.1, the target strength was determined as 30MPa, derived from Table 3.2 (Defective Level & Constant k).

Table **Error! No text of specified style in document.-11**: Defective level and Constant K for cement (BRE manual)

Defective Level	Constant (k)
1%	2.33
2.5%	1.96
5%	1.64

3.2.3 Selection of water/cement ratio

Table **Error! No text of specified style in document.-12**: Approximate compressive strength of concrete of water/cement ratio of 0.5 according to the 1988 British method (DOE)

Approximate Compressive Strength of concrete made with a free Water/cement ratio of 0.5. According to the 1988 British method (DOE).					
Type of cement	Type of CA	Compressive strength at the age (cube)			
		3	7	28	91
OPC (Type I)	Uncrushed	22	30	42	49
Sulphate Resisting Cement (Type V)	Crushed	27	36	49	56
Rapid Hardening Portland Cement (Type III)	Uncrushed	29	37	48	54
	Crushed	34	43	55	61

Referring to Table 3.3, for OPC, uncrushed aggregates, at 28 days, the compressive strength was determined as 42MPa.

A dotted line curve was drawn parallel to the surrounding curve after finding an intersection point for the compressive strength and water/cement ratio from Figure 3.1. Using the graph, a water/cement ratio of 0.6 for a target mean strength was obtained.

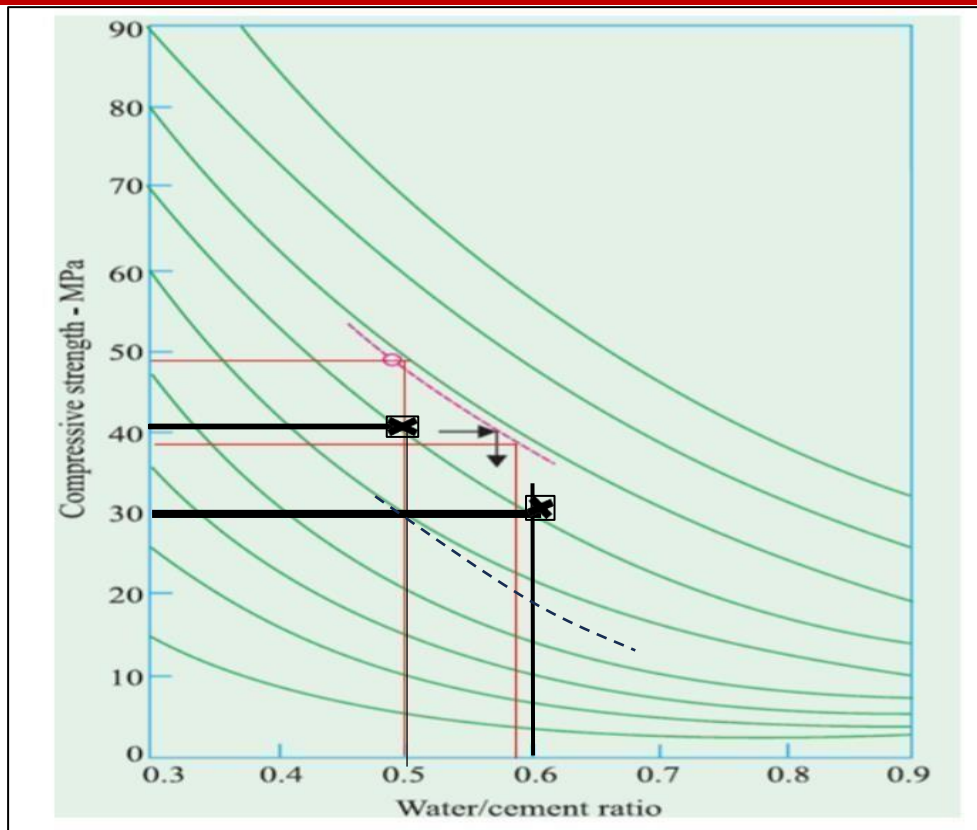


Figure Error! No text of specified style in document..15: Compressive strength vs. free-water/cement ratio graph

3.2.4 Calculation of water content

Based on Table 3.4, with a slump of 60–180mm and 20mm max aggregate size, mixing water content was 225kg/m³.

Table Error! No text of specified style in document.-13: Approximate free water contents for workability (Eren, n.d.)

Approximate free-water contents (kg/m ³) required to give various levels of workability					
Slump (mm)		0 - 10	10 - 30	30 - 60	60 - 180
Vebe time (s)		> 12	6 - 12	3 - 6	0 - 3
Maximum size (mm)	Type of aggregate				
10	Uncrushed	150	180	205	225
	Crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	Crushed	170	190	210	225
40	Uncrushed	115	140	160	175
	Crushed	155	175	190	205

3.2.5 Cement content

$$\text{Cement content} = \text{free water content} \div \text{free water- cement ratio} \quad (3.2)$$

Using Equation 3.2, cement content = $225 \div 0.6 = 375\text{kg/m}^3$, exceeding the BS 8110:1–1985 minimum of 350kg/m^3 .

3.2.6 Total Aggregate Weight

$$\text{Aggregate content at Saturated Surface Dry (SSD)} = D - C - W \quad (3.3)$$

Where D represents the wet density of concrete, C represents the cement content, and W represents the water content. (Gentilini et al., 2015).

With SSD of 2.67 and w/c of 0.6, the concrete wet density from Figure 3.2 was read as 2370kg/m^3 .

$$\text{Total Aggregate content at SSD} = 2370 - 375 - 225 = 1770\text{ kg/m}^3$$

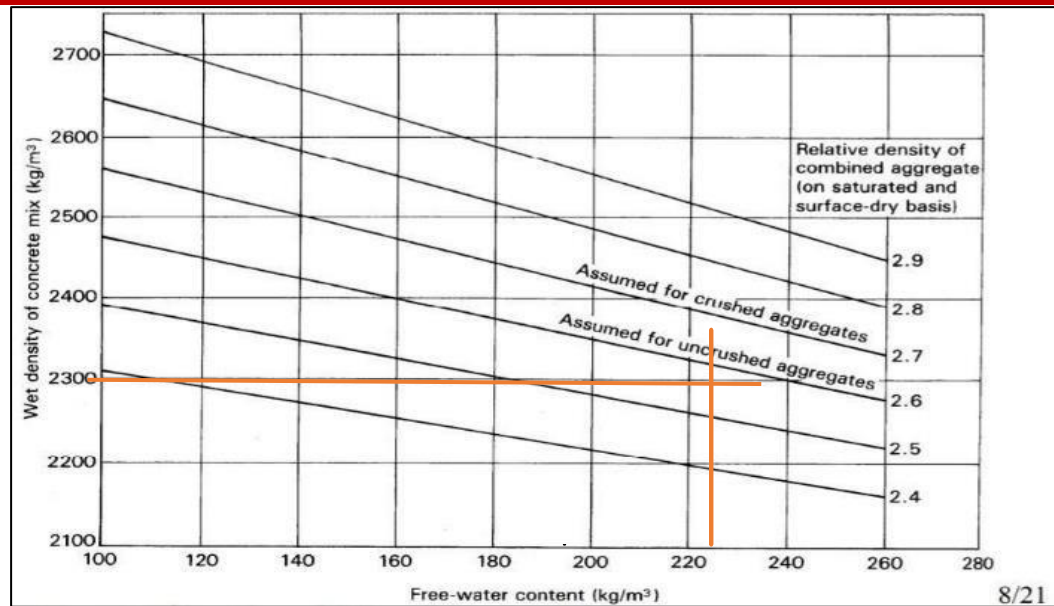


Figure Error! No text of specified style in document..16 Relative density of combined aggregates on saturated surface dry

3.2.7 Weight of Fine Aggregates

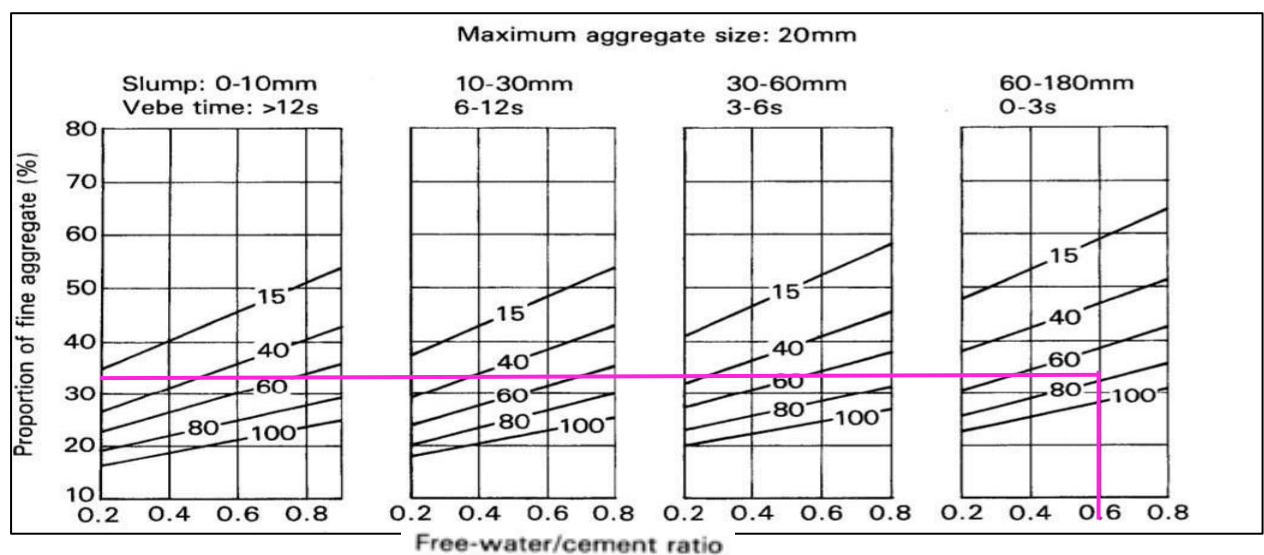


Figure Error! No text of specified style in document..17: Proportion of fine aggregates (%) against free water/cement ratio

The fine aggregate proportion from figure 3.3, recorded as 38%, was used to determine the fine and coarse aggregate content, following equations 3.4 and 3.5.

$$\text{Fine aggregate content} = \text{Total aggregate content} * \text{the proportion of fine aggregates} \quad \dots\dots\dots (3.4)$$

$$\text{Fine aggregate content} = 1770 * 0.38 = 672.6 = 673 \text{ kg/m}^3$$

$$\text{Coarse aggregate content} = \text{Total aggregate content} - \text{Fine aggregate content} \quad \dots\dots\dots (3.5)$$

Coarse aggregate content = $1770 - 673 = 1097 \text{ kg/m}^3$

3.2.8 Proportions

Table 3.14: Proportions of a control mix sample

Ingredients	Cement	Fine aggregate	Coarse Aggregate	Water
Quantity Kg/m ³	375	673	1097	225
Ratio	1.00	1.8	2.9	0.6

A control mix (M1) was prepared with a 2.9:1.8:1 ratio of coarse aggregates, fine aggregates, and cement. In other mixes, 50% RA replaced coarse aggregates, while pumice partially replaced cement at 10, 20, 30, 40, and 50% by volume as illustrated in Table 3.5.

Table 3.15 The % of added materials in the various samples

Mixes	Cement	Fine aggregates	Coarse aggregates	Recycled aggregates	Powdered pumice
M0(control)	100%	100%	100%	-----	-----
M1	100%	100%	50%	50%	-----
M2	90%	100%	50%	50%	10%
M3	80%	100%	50%	50%	20%
M4	70%	100%	50%	50%	30%
M5	60%	100%	50%	50%	40%
M6	50%	100%	50%	50%	50%

3.3 Laboratory Tests

Various laboratory tests were conducted on raw materials, fresh, and hardened concrete. Aggregates, including recycled ones, were tested for shape, size, and strength (BS EN 12620), while pumice powder was analyzed for chemical composition, particle size, and specific gravity. Fresh concrete tests (BS EN 12350) assessed workability through slump, compaction, and density. Hardened concrete was evaluated for compressive strength (BS EN 12390-3), tensile strength (BS EN 12390-6), density (BS EN 12390-7), water absorption (BS 1881-122), and permeability (BS EN 12390-8). SEM was used for microstructural analysis.



Figure 3.18: Recycled Aggregates (RA) and normal coarse Aggregates

4. Results, Analysis and Discussion

4.1 Results

4.1.1: Physical Properties of Raw Materials

The tests conducted on the raw materials were essential to evaluate their characteristics and ensure they meet the requirements for producing high-quality concrete. The physical properties of the raw materials are summarized in Table 4.1

Table 4.1 Physical Properties of Raw Materials

	Fine Aggregate	Coarse Aggregate	RAC	Pumice
Saturated Surface Dried (SSD) (g)	456.1	506.6	980.0	1064.0
Pycnometer + Water + SSD (g)	1880.8	1918.8	1420.0	1450.0
Pycnometer + Water (g)	1611.3	1611.3	1210.0	1230.0
Oven Dried (g)	446.1	491.6	940.0	950.0
Water Absorption (%)	2.24	3.06	8.50	12.0
Specific Gravity	2.53	2.64	2.10	0.65
Density (kg/m ³)	1675	1500	1300	500
Moisture Content (%)			6.0	
Aggregate Crushing Value (%0		14.25	18.50	

Sieve analysis results demonstrated that all aggregates exhibit suitable particle size distributions for concrete production. The fine aggregates are well-graded for workability, and the coarse aggregates provide strength and stability making them ideal for the intended concrete mix designs.

4.1.2 Results of Fresh Concrete Tests

Slump value, compaction factor and density of the fresh concrete are presented in table 4.5

Table 4.5: Results of Fresh Concrete Tests

Mix	Slump Value	Compaction Factor	Density (kg/m ³)	Water Absorption (%)
M0 (control)	103	0.75	2320.99	4.67
M1	98	0.71	2286.42	4.73
M2	89	0.96	2261.73	4.96
M3	85	0.96	2242.59	5.63
M4	90	0.97	2202.47	5.67
M5	80	0.92	2192.59	5.52
M6	72	0.89	2187.04	5.31

High 0.95–1.00, Medium 0.85–0.95, Low 0.80–0.85, Very low 0.78

Corresponding graphs are presented in figures 4.1 to 4.3.

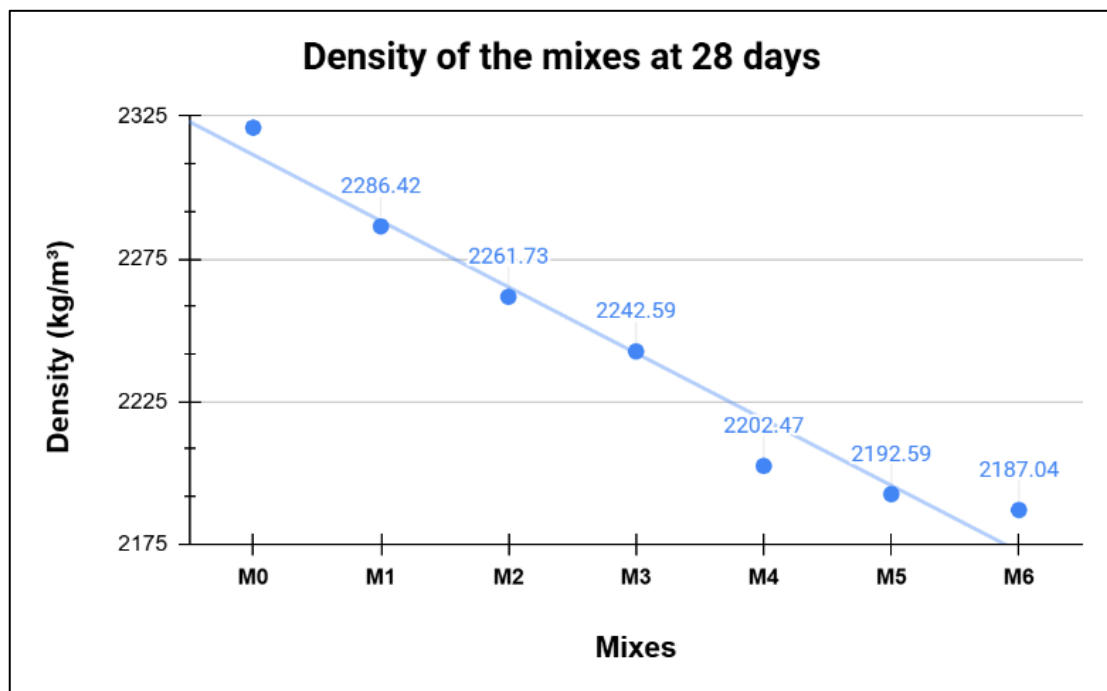


Figure 4.1: Density of the concrete mixes

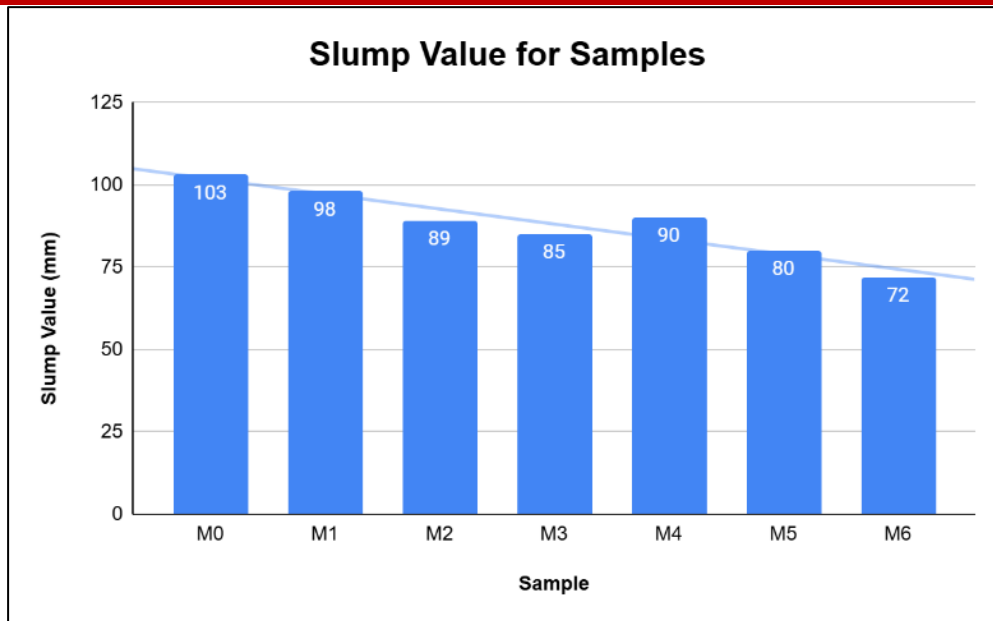


Figure 4.2: Slump Value (mm) graph

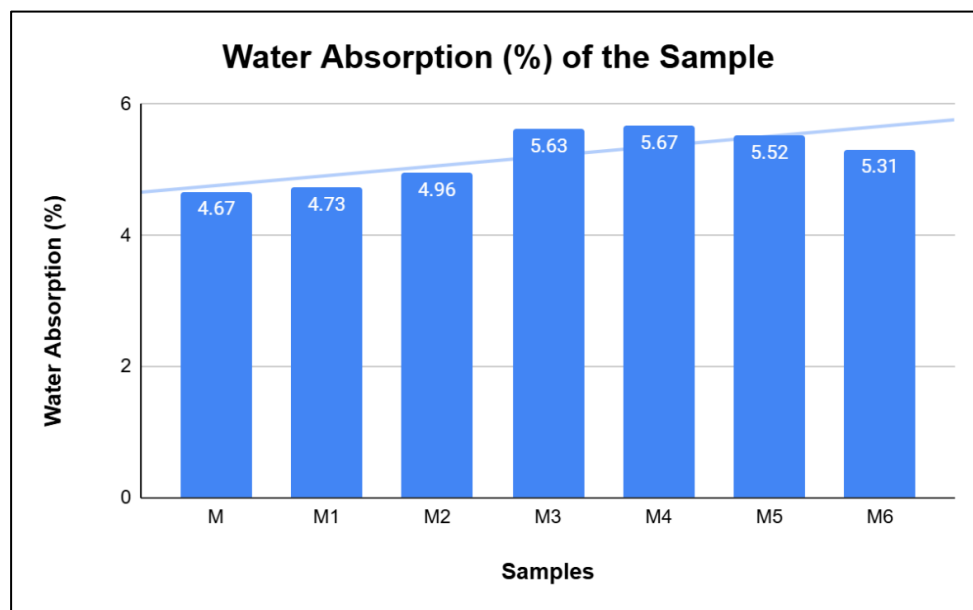


Figure 4.3: Samples Water absorption (%) at 28 days

The results confirm all mixes are workable and suitable for concrete production. M1 has a higher slump (103mm vs. 89mm for M0) but lower compaction (0.71 vs. 0.75), indicating increased flowability but reduced densification. RA improves workability, while pumice lowers density, affecting compaction. Concrete density decreases as pumice content increases, with M6 recording the lowest at 2187.04 kg/m³, reflecting pumice's lightweight nature. Water absorption rises with pumice incorporation, exceeding 5% for replacements of 20% and above.

4.1.3 Mechanical Properties of Hardened Concrete

A Table of Compressive and Tensile strength at 28 days for the concrete samples are presented in table 4.8.

Table 4.8: Compressive and Tensile Strengths at 28days

Mixes	Compressive Strength (MPa)	Tensile Strength (MPa)
M0	40.33	2.094
M1	41.57	2.585
M2	32.57	2.653
M3	28.66	2.761
M4	23.25	1.922
M5	22.29	1.850
M6	14.29	2.038

Pumice-modified mixes (M2–M6) showed reduced compressive strength compared to M0 and M1. M2 (10% pumice) performed best, reaching 32.57 MPa. Based on the graph, pumice replacement up to 19.42% attained 30 MPa, meeting target strength of class 25/20 concrete. Decline in strength beyond 19.42% pumice was due to increased porosity and reduced bonding efficiency in the cement matrix. Tensile strength slightly increased up to M3 with 20% pumice, then decreased as pumice content increased further.

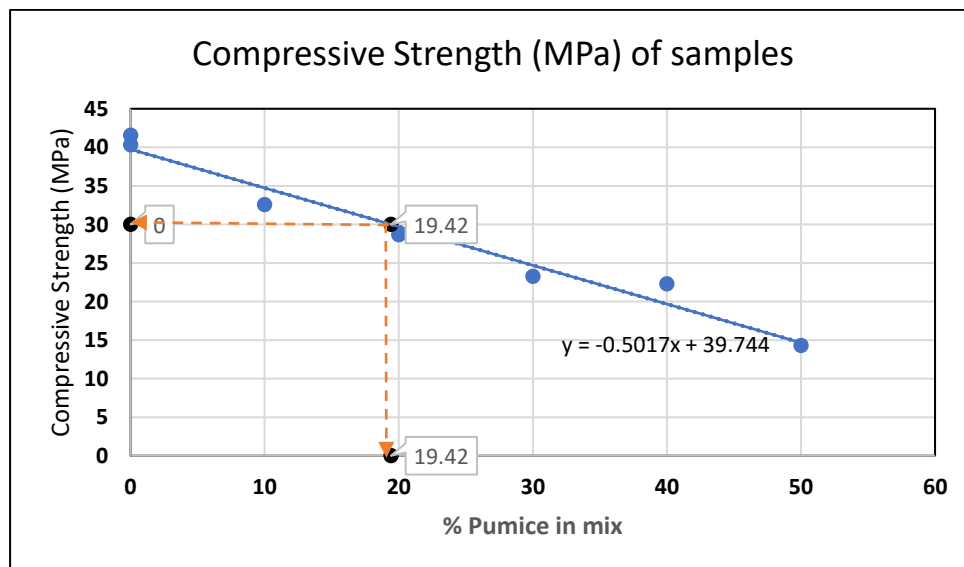


Figure Error! No text of specified style in document..7: Compressive Strength (MPa) of the mixes at 28 days

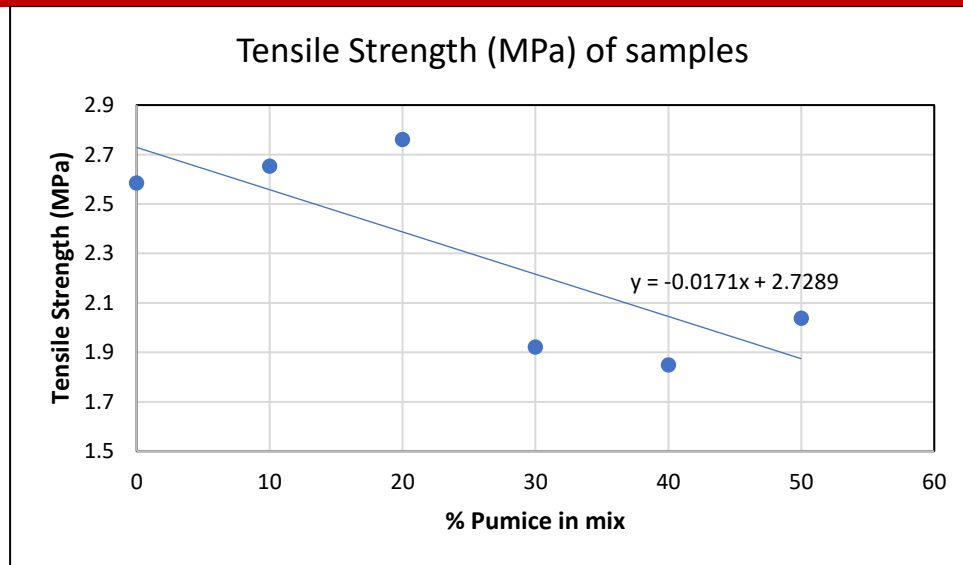


Figure Error! No text of specified style in document..8: Tensile strengths of the mixes 28days

4.1.4 Microscope images

Light microscopy images in Figures 4.9 to 4.12 provide a general visual overview of the samples.

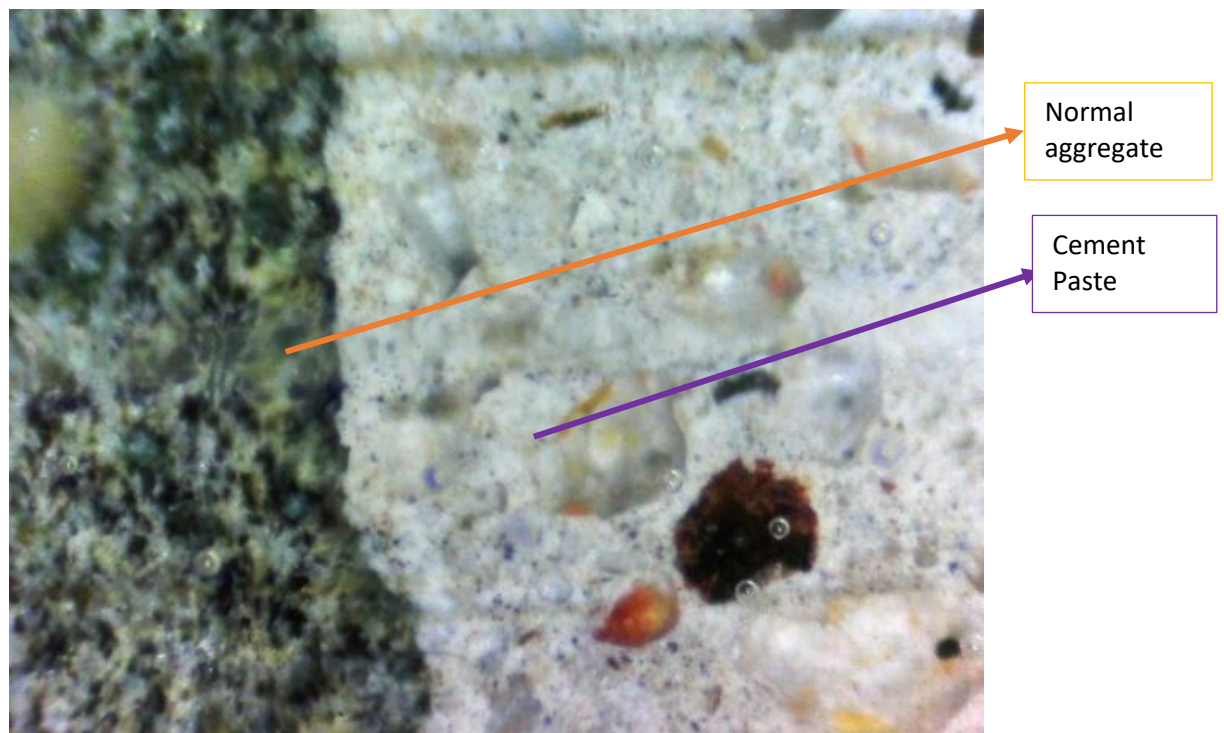


Figure4.9: M0 – Sharp boundary between aggregate surface and bulk cement paste, indicating low void content near the aggregate

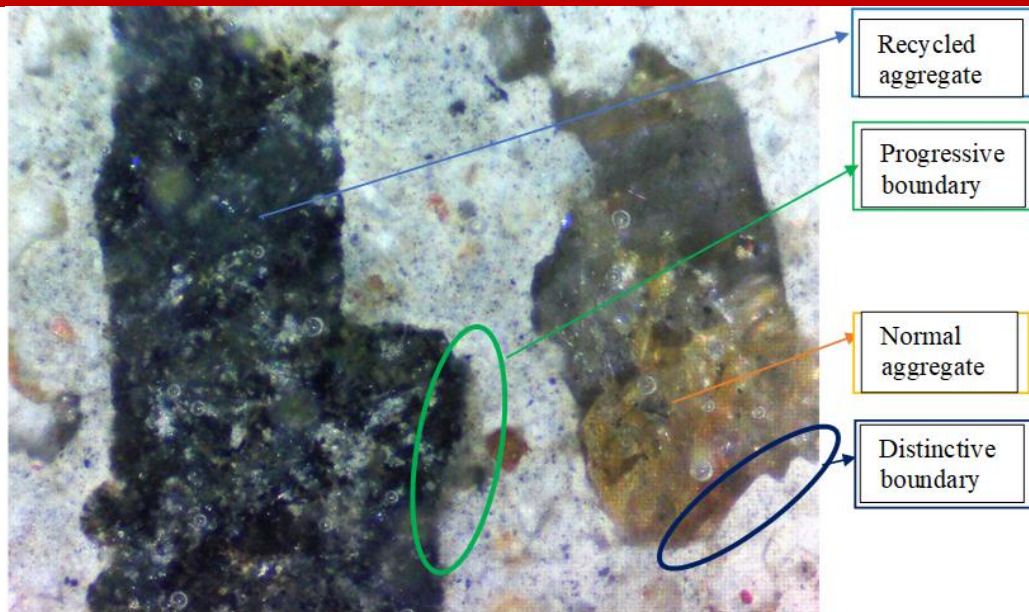


Figure 4.10: M1 – Progressive boundary around recycled aggregates unlike the distinctive boundary in a normal aggregate

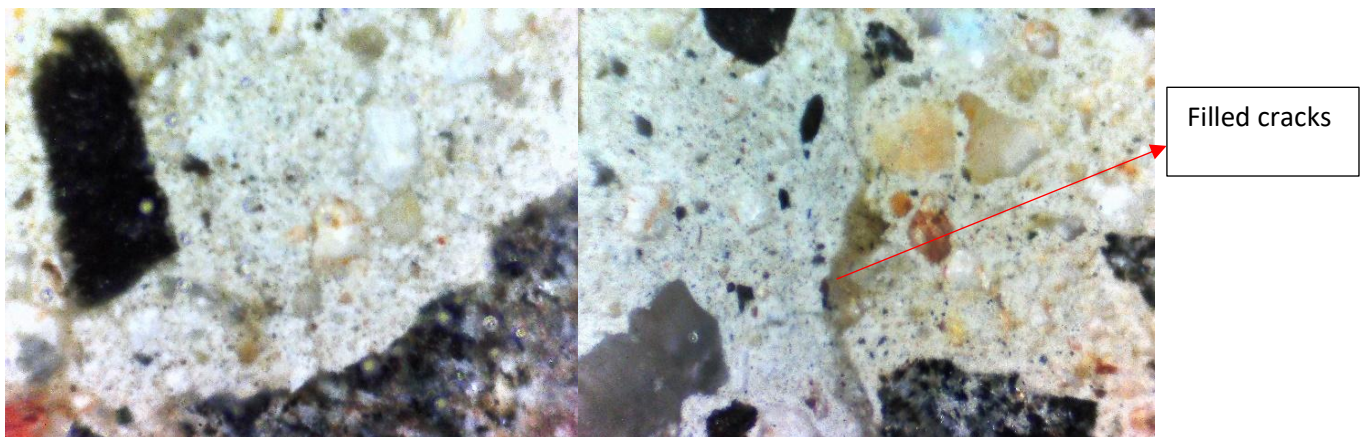


Figure 4.11: M2 – Introduction of pumice powder into the mix filling cracks

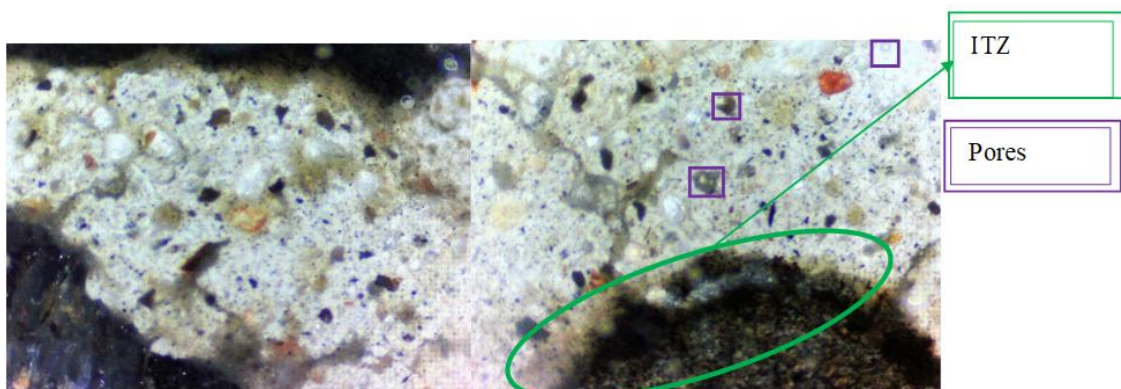


Figure 4.12: M3 – Pumice powder filling voids and interfacial transition zones (ITZ) around recycled aggregates

4.1.5 Scanning Electron Microscope images

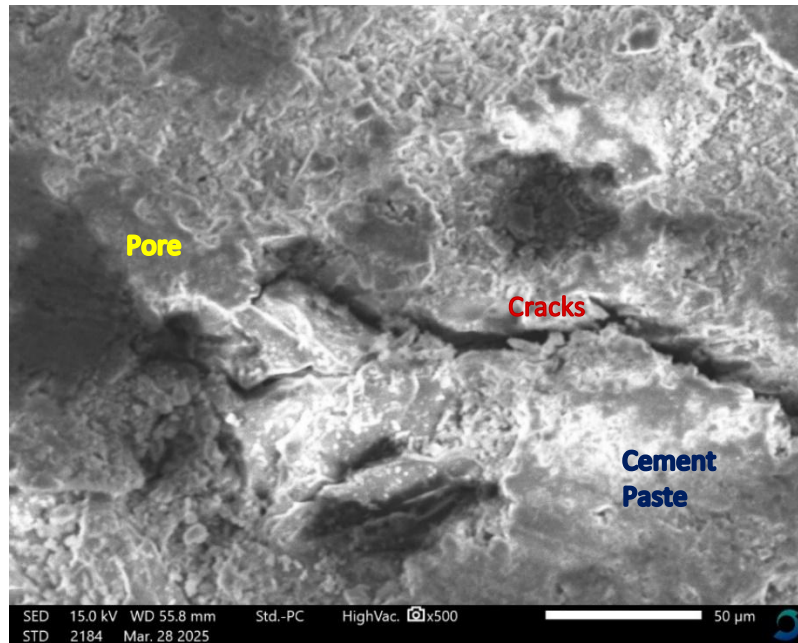


Figure 4.119: M1 Cracks propagating from the pores

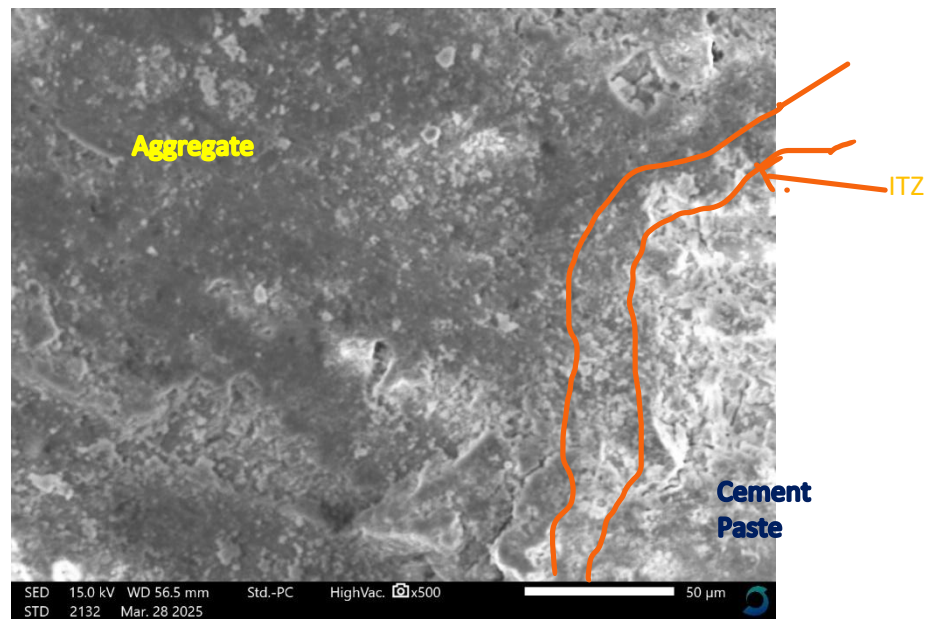


Figure 4.120: M2 improved bonding in the ITZ region with addition of pumice

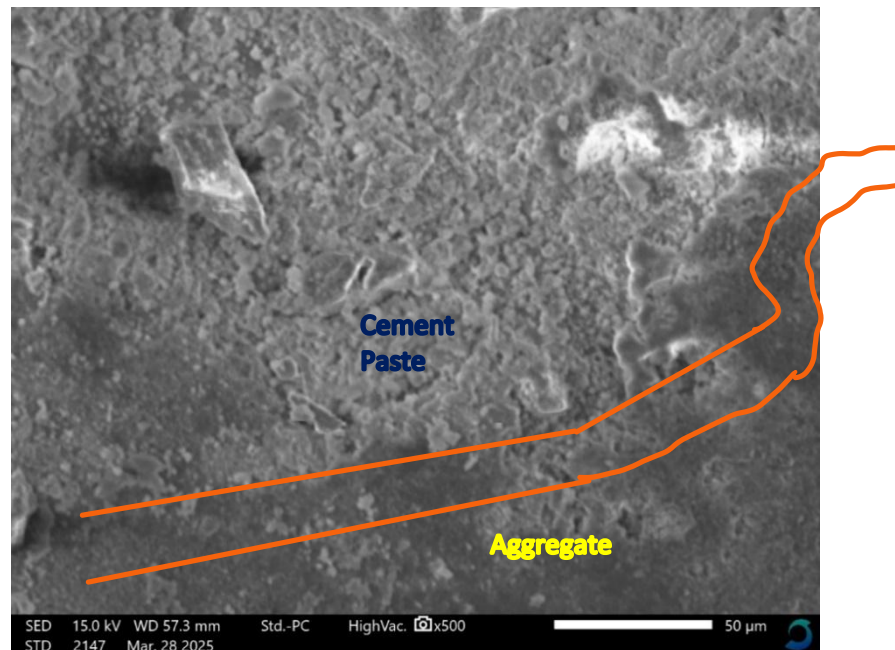


Figure 4.121: M3 Well bonded ITZ

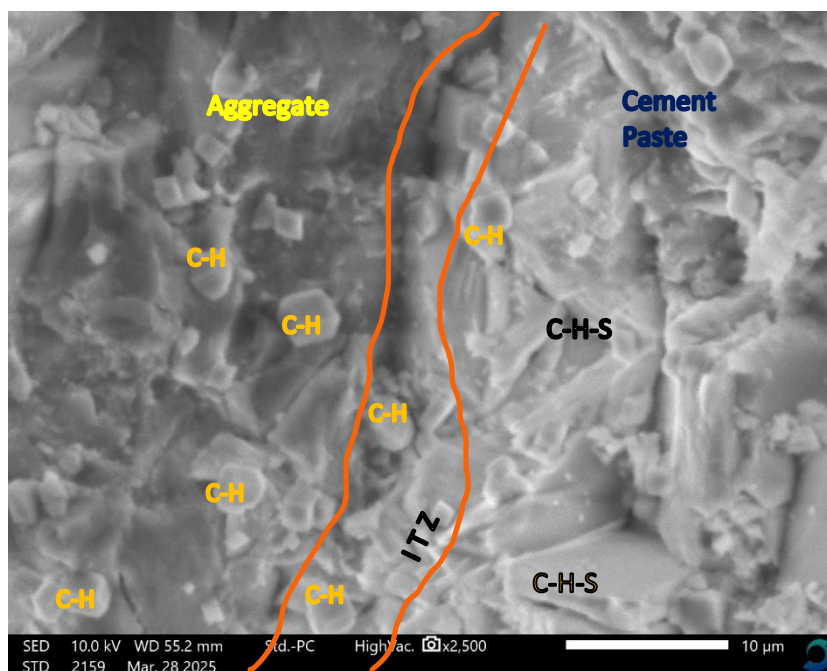


Figure 4.122: M4 deficient CaO leading to unreacted calcium hydroxide C-H which would otherwise enhance bonding

Scanning Electron Microscope images reveal M1 exhibits large crack propagation from pores and around recycled aggregates, M2 shows improved ITZ bonding with pumice, M3 has a well-bonded ITZ, while M4–M6 display deficient CaO, leading to unreacted calcium hydroxide (C-H), weakening bonding in the ITZ region.

4.2 Discussion

4.2.1 Properties of the Raw Materials

The properties of powdered pumice, recycled aggregates (RA), natural aggregates, and cement significantly influenced concrete performance. RA exhibited high water absorption (94.12%) due to retained cement paste and microcracks, requiring pre-soaking to enhance moisture distribution and consistency. With a specific gravity of 2.23, RA was lighter than natural aggregates (2.54), making it suitable for lightweight concrete, though its porous nature required mix adjustments for strength and workability. Powdered pumice (SG 0.65, 12% water absorption) contained high aluminium oxide (74.32%) and silicon dioxide (16.75%), reinforcing pozzolanic reactions that improve concrete bonding. These oxides enable pumice to react with calcium hydroxide during cement hydration, forming strength-enhancing gels like C-S-H and C-A-H. While its low bulk density (500 kg/m³) helped reduce concrete weight, its high porosity increased water demand, which necessitated careful mix design to balance strength and workability.

4.2.2 Performance of the Newly Developed Composite

4.2.2.1 Physical Properties Analysis

All modified mixes had lower slump values (98–72mm) than M0, indicating reduced flowability due to the high porosity and absorption capacity of RA and pumice, which retained more water, limiting its availability for lubrication. Despite this, M2–M4 exhibited high compactability (0.96–0.97) due to RA's angular shape and interlocking ability, enhancing particle bonding. In contrast, M5 and M6 recorded lower compaction (0.92–0.89) as pumice's lightweight, porous nature disrupted mix cohesion. Density decreased across all mixes, with M6 (2187.04 kg/m³) showing the lowest, as pumice replaced heavier cement particles, reducing overall weight while maintaining volume. Water absorption increased across all mixes, especially in M3 and M4 (5.63–5.67%) due to pumice's high porosity and moisture retention. The results confirm that RA improves compactability, while pumice lowers density and increases absorption, requiring careful proportioning to maintain durability.

4.2.2.2 Mechanical Properties Analysis

RA enhanced strength, as M1 outperformed M0 in compressive (41.57 vs. 40.33 MPa) and tensile strength (2.585 vs. 2.094 MPa) due to improved internal bonding. However, increasing

pumice content (M2–M6) steadily reduced compressive strength, with M2 (10% pumice) achieving 32.57 MPa, remaining within the acceptable range for class 25/20 concrete. Strength dropped sharply beyond 19.42% pumice, reaching 14.29 MPa in M6, due to high porosity and low CaO, which weakened C-S-H and C-A-H formation. Tensile strength peaked at 2.761 MPa in M3 (20% pumice) due to enhanced crack resistance, but further pumice replacement led to weaker bonding and interfacial zones. These results confirm RA can be used without strength loss, while pumice should be limited to $\leq 19.42\%$ for structural applications.

4.2.3 Characterization of the ITZ region

The ITZ region was significantly affected by RA and pumice incorporation. In M0, the ITZ was dense and well-bonded, ensuring low porosity and strong hydration, but M1 exhibited cracks and voids due to residual mortar, weakening cohesion. M2–M3 (10–20% pumice replacement) improved ITZ quality, as pumice filled voids, enhancing bonding and microstructure. However, in M4 and above, low CaO levels led to unreacted calcium hydroxide (CH) hence poor bonding, increasing porosity and early-age cracking. Moderately pumice-modified mixes (M2–M3) performed better than M1, closely matching M0's integrity, while higher pumice levels ($>30\%$) reduced hydration, compromising durability.

5. Conclusions and Recommendations

5.1 Conclusion

1. **Raw Material Properties:** RA and pumice had lower density and higher porosity than natural aggregates, reducing concrete density but improving suitability for lightweight applications. Pumice's high water absorption increased water demand, requiring precise mix adjustments for workability.
2. **Composite Performance:** Partial replacement of cement with Pumice up to 19.42% maintained adequate compressive strength, meeting class 25/20 concrete requirements. Strength declined beyond 19.42% due to higher porosity and insufficient CaO, limiting pozzolanic reactions and reducing C-S-H and C-A-H formation.
3. **ITZ Characterization:** Moderate pumice content (M2–M3) improved ITZ quality, enhancing void filling and bonding, while pumice above 30% weakened matrix cohesion, increasing porosity and cracking risk. Keeping pumice below 20% preserved ITZ integrity and enhanced durability.

An optimal 19.42% pumice replacement effectively reduced cement consumption while ensuring structural performance, creating durable, lightweight concrete using recycled materials.

5.2 Recommendations

5.2.1 Recommendations from this Study

1. Limit pumice substitution to 19.42% to prevent excessive porosity and reduced matrix cohesion of structural concrete while still benefiting from its lightweight properties and pozzolanic reactivity.
2. Pre-saturate recycled aggregates before mixing to reduce water absorption, preventing excessive void formation and improving matrix cohesion and ITZ integrity.
3. Implement strict quality control for RA, including grading, washing, and crushing refinement, to enhance material consistency and mitigate strength reductions caused by residual mortar.
4. Promote pumice-modified RAC for lightweight applications, such as load-bearing elements and moderate-load structures, supporting sustainable construction without compromising mechanical performance.

5.2.2 Recommendations for Further Study

1. Assess long-term durability, including creep, chloride penetration, freeze-thaw cycles, and carbonation effects.
2. Analyse pumice with other SCMs like fly ash and slag to explore combined effects on concrete properties.
3. Conduct life-cycle assessments to quantify environmental and economic benefits of pumice-modified RAC.
4. Study ITZ evolution using advanced imaging (XRD) to examine bonding, crack resistance, and degradation.

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