

Multi-Response Optimisation of PVC-Based Composites Properties for Sustainable Applications

Chinecherem Chinenye Ikelugo¹, Oluwaseyi Omotayo Taiwo^{1*}, Samuel Mary Obioarah¹, Ukamaka Ezeobi¹

¹Department of Metallurgical and Materials Engineering, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria.

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Corresponding Author:

Oluwaseyi Omotayo Taiwo

oh.nnalue@coou.edu.ng

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Abstract: This study reports the development and multi-response optimisation of poly(vinyl chloride) (PVC) hybrid composites reinforced with coconut fibre and corncob ash for sustainable, low-load applications. Nine hybrid formulations, combining 3-10 wt.% coconut fibre and 3-10 wt.% corncob ash with a balance of PVC, were fabricated by compression moulding and evaluated for tensile strength, hardness, flexural strength and water absorption; the constituent materials and composites were further characterised by Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD) and scanning electron microscopy (SEM). FTIR confirmed a hydrophobic, carbon-chlorine-rich PVC backbone, a hydroxyl-rich lignocellulosic coconut fibre and a siliceous corncob ash, indicating a physically compatible but chemically dissimilar hybrid system. SEM micrographs linked dense, well-wetted microstructures to superior hardness and flexural performance, whereas fibre pull-out cavities and heterogeneous interfaces corresponded with reduced tensile strength and higher water uptake, while XRD confirmed persistent, quartz-dominated crystalline phases that intensified with ash loading. Reinforcement reduced tensile strength from 55.46 MPa (control) to between 19.27 and 36.89 MPa, but increased hardness (up to 34.54 HV, +76.2%) and flexural strength (up to 41.79 MPa, +216.1%) relative to neat PVC, while water absorption rose from 0.60% to a maximum of 1.90%. A mixture-design, desirability-function optimisation that simultaneously maximised flexural strength and hardness while minimising water absorption identified a global optimum of 88.40 wt.% PVC, 5.95 wt.% coconut fibre and 5.66 wt.% corncob ash, predicting 32.14 MPa flexural strength, 29.11 HV hardness and 1.36% water absorption (composite desirability = 0.560). Benchmarked against recent PVC- and polymer-based natural-filler composites, this balanced formulation is proposed for non-load-bearing interior cladding, demonstrating a scientifically defensible route for valorising agricultural residues within sustainable PVC composite design.

Keywords: Coconut fibre; Corncob ash; Desirability function; Multi-response optimisation; PVC composites; Sustainable materials.

Introduction

Poly (vinyl chloride) (PVC) remains one of the most widely produced thermoplastics because of its low cost, chemical resistance and processing versatility, yet its sustainability profile is constrained by dependence on petrochemical feedstock and by a formulation complexity that complicates end-of-life recycling

(Lewandowski & Skórczewska, 2022; Jha et al., 2024). At the same time, agricultural and agro-processing residues such as coconut husk and corncob are generated in large volumes worldwide and are frequently underutilised, representing both an environmental burden and an untapped source of low-cost reinforcement for polymer composites (Gairola et al., 2022; Mohammed et al., 2022). Converting these residues into functional fillers for PVC

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therefore addresses two sustainability objectives at once: it reduces the proportion of virgin polymer required per unit product, and it diverts biomass residue from open burning or landfill into a value-added material stream.

Coconut fibre (coir) and corncob ash are attractive candidates for hybridisation in a PVC matrix because they provide complementary reinforcing mechanisms. Coir is a lignocellulosic fibre with substantial lignin content that contributes crack-bridging and bending resistance, whereas corncob ash, obtained by controlled combustion of corncob residue, is a siliceous mineral particulate that restricts local matrix deformation and improves surface hardness (Madueke et al., 2024; Sathiparan, 2025). Because PVC presents a relatively non-polar, chlorinated backbone while coir is hydroxyl-rich and moisture-sensitive, the fibre-matrix interface is chemically mismatched, and untreated hybrid systems commonly display trade-offs between mechanical reinforcement and moisture resistance (Putra et al., 2020; Boussehel et al., 2024).

A central difficulty in designing such hybrid systems is that no single formulation simultaneously maximises every desirable property: increasing total reinforcement content tends to improve stiffness-related responses such as hardness and flexural strength while degrading tensile continuity and raising water uptake. Selecting a formulation on the basis of one property in isolation can therefore yield a material that performs well in one respect but poorly in service. This motivates multi-response, desirability-based optimisation, which has been applied successfully to balance competing properties in other natural-fibre and mixture-based composite systems (Zerin et al., 2022; Nadondu et al., 2022; Benyettou et al., 2023).

This article discusses the results of an investigation into PVC hybrid composites reinforced with coconut fibre and corncob ash, focusing specifically on the properties most relevant to establishing structure-property relationships and to enabling multi-response formulation optimisation: tensile strength, hardness, flexural strength and water absorption, together with Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD) and scanning electron microscopy (SEM) characterisation of the constituent materials and composites. The mixture-design optimisation results, which balance flexural strength, hardness and water absorption through a desirability function, are then discussed in order to identify a formulation suitable for sustainable, non-load-bearing applications. The objective is to demonstrate a scientifically defensible and reproducible route for converting coconut fibre and corncob ash into a balanced PVC hybrid composite for low-load, sustainability-driven product design.

Materials and reinforcement preparation

Commercial-grade poly(vinyl chloride) resin was used as the polymer matrix. Coconut fibre (coir) was obtained by manual de-fibring of coconut husk following seven days of water retting, after which the fibres were washed and sun-dried to a moisture content below 5%. Corncob ash was produced by cleaning and drying corncob residue, followed by controlled combustion in a muffle furnace (heating rate ≈ 10 °C/min to 600 °C, held for 2 h), and subsequent pulverisation and sieving through a 300 μm mesh to obtain a particulate reinforcement of relatively uniform size.

Composite formulation and fabrication

Coconut fibre and corncob ash were incorporated into the PVC matrix at 3, 5 and 10 wt.% each, generating nine hybrid formulations (C1-C9) in addition to an unreinforced PVC control, as summarised in Table 1. The constituents were dry-blended according to the design matrix and consolidated by compression moulding under controlled temperature, pressure and dwell time, after which the moulded sheets were cooled under controlled conditions and machined into specimens of the dimensions required by the relevant test standards.

Table 1. Experimental formulation matrix of the control and hybrid PVC composites.

Sample	Coconut fibre (wt.%)	Corncob ash (wt.%)	PVC (wt.%)
Control	0	0	100
C1	3	3	94
C2	3	5	92
C3	3	10	87
C4	5	3	92
C5	5	5	90
C6	5	10	85
C7	10	3	87
C8	10	5	85
C9	10	10	80

Note. Sample codes C1-C9 are used consistently throughout the tables and text

Mechanical and physical testing

Tensile properties were determined in accordance with ASTM D638 (ASTM International, 2022b) using a universal testing machine (UTM) with dumbbell-shaped specimens loaded to fracture at the standard crosshead speed; tensile strength was taken as the maximum stress sustained before failure. Flexural properties were determined by the three-point bend method in accordance with ASTM D790 (ASTM International, 2025), using rectangular specimens supported on two rollers with a centrally applied load; flexural strength was calculated from the maximum load recorded during

bending. Hardness was measured with a Shore durometer in accordance with ASTM D2240 (ASTM International, 2021), with the indenter applied perpendicular to a flat specimen surface after the specified dwell time; consistent with the original experimental dataset, hardness values are reported in HV units. Water absorption was determined in accordance with ASTM D570 (ASTM International, 2022a): oven-dried specimens (60 °C to constant mass) were weighed (W_0), immersed in distilled water at approximately 23 ± 2 °C for the specified period, surface-dried and reweighed (W_t), and the percentage water absorption calculated as $[(W_t - W_0)/W_0] \times 100$. At least three specimens were tested per formulation and mean values reported.

Structural and morphological characterisation

FTIR spectra of the PVC matrix, coconut fibre, corncob ash and selected composites were acquired using an ATR-equipped FTIR spectrometer over the range 4000-400 cm^{-1} at 4 cm^{-1} resolution, with baseline correction applied before peak assignment. XRD patterns were acquired using Cu-K α radiation ($\lambda \approx 1.5406$ Å) over a 2θ range of approximately 5-80° on pulverised, homogenised samples, with diffractograms background-corrected and peaks matched against reference crystallographic patterns. SEM was performed on fractured surfaces of selected composites, sputter-coated with a thin conductive layer, at accelerating voltages of 5-20 kV, to examine fibre-matrix adhesion, particle dispersion, voids and fibre pull-out features.

Multi-response optimisation

A mixture-design approach was used to relate the fractions of PVC, coconut fibre and corncob ash to the measured responses. The Cox response trace tool, implemented in the mixture-methodology module of Minitab 15, was used to visualise the predicted effect of varying each component proportionally relative to the design centroid while respecting the mixture constraint that the three components sum to 100%. Flexural strength and hardness were set as maximisation objectives and water absorption as a minimisation objective, each assigned equal weight and importance (Table 12). Individual response desirabilities (0 = unacceptable, 1 = target achieved) were combined geometrically into a composite desirability, and the formulation maximising composite desirability was identified as the global optimum; an additional local solution at the upper reinforcement boundary was also evaluated for comparison.

Results and Discussion

FTIR spectral characterisation of the constituent materials

1. PVC matrix

The FTIR spectrum of the neat PVC displayed the expected fingerprint of a chlorinated vinyl polymer: aliphatic C-H stretching bands near 3000-2850 cm^{-1} , CH₂ deformation/wagging bands at 1430-1330 cm^{-1} , a C-H deformation feature near 1250 cm^{-1} , and prominent C-Cl stretching bands between 700 and 600 cm^{-1} , the diagnostic signature of the PVC backbone (Table 2). No broad hydroxyl absorption was observed, confirming the relatively non-polar, hydrophobic character of the PVC matrix. This chemical contrast with the hydroxyl-rich lignocellulosic reinforcement is significant because it establishes, from the outset, a polarity mismatch at the fibre-matrix interface; without adequate drying, dispersion and pressure-assisted wetting, this mismatch can generate interfacial voids that compromise tensile performance (Section Tensile strength). Nonetheless, the polar C-Cl bonds of PVC can interact with oxygen-containing fillers through dipolar attraction and secondary bonding even without covalent reaction, consistent with reports that surface modification and processing state strongly influence interfacial morphology and mechanical performance in PVC/plant-fibre and PVC/wood systems (Boussehel et al., 2024; Li et al., 2022).

2. Coconut fibre

The coconut-fibre spectrum exhibited the characteristic bands of a lignocellulosic material: a broad O-H stretching band at 3500-3200 cm^{-1} arising from cellulose, hemicellulose, lignin and adsorbed moisture; aliphatic C-H stretching near 2920 cm^{-1} ; carbonyl-related features at 1740-1700 cm^{-1} associated with hemicellulose and waxy or ester surface constituents; aromatic lignin skeletal vibrations at 1600-1500 cm^{-1} ; CH₂ bending and C-H deformation bands near 1420 and 1370 cm^{-1} ; C-O-C/C-O stretching of polysaccharides at 1250-1000 cm^{-1} ; and a band near 900 cm^{-1} associated with β -glycosidic linkages in cellulose. These features confirm a cellulose-rich fibre with appreciable hemicellulose and lignin content. The broad hydroxyl band is functionally ambivalent: it supports intramolecular hydrogen bonding that contributes to fibre stiffness, but it also renders the fibre intrinsically hydrophilic, providing a direct spectroscopic explanation for the systematic rise in composite water absorption with increasing coconut-fibre loading discussed in Section Water absorption. The relatively strong lignin-related bands are consistent with the known toughness of coir and support the crack-bridging role that coconut fibre plays in the flexural response of

the composites (Section Flexural strength). These findings parallel reports that coir-surface condition governs fibre-matrix adhesion and that controlled surface treatment measurably alters both functional-group chemistry and interfacial performance in coir-reinforced systems (Putra et al., 2020; Camillo et al., 2023).

3. Corncob ash

The corncob-ash spectrum differed substantially from that of the raw fibre because controlled combustion removes most organic polysaccharide constituents and concentrates inorganic oxide and mineral residues. A weak, broad band near $3500\text{--}3200\text{ cm}^{-1}$ was attributed to residual surface hydroxyl groups and adsorbed moisture; a feature near 1600 cm^{-1} was associated with bending of adsorbed water and residual carbonaceous groups; the dominant absorption at approximately $1100\text{--}900\text{ cm}^{-1}$ was assigned to Si-O and Si-O-Si stretching in siliceous phases; and bands below approximately 800 cm^{-1} were associated with silica bending and metal-oxygen modes. These assignments confirm that properly combusted corncob ash behaves primarily as an inorganic, silica-dominated particulate rather than as an untreated lignocellulosic powder, consistent with reports that corncob-derived ash contains substantial silica together with variable alumina, iron, calcium, magnesium and potassium oxide fractions (Sathiparan, 2025; Gandam et al., 2022). This siliceous, rigid character is central to explaining the hardness improvements associated with ash addition (Section Hardness), while residual surface hydroxyl groups provide a possible secondary interaction pathway with both the PVC matrix and the coconut-fibre surface (Mulana et al., 2024).

4. Compatibility implications

Table 2 summarises the principal FTIR bands identified in each constituent and their implications for composite behaviour. Collectively, the spectra indicate a physically compatible but chemically dissimilar three-phase hybrid system: PVC provides the continuous, weakly polar thermoplastic phase; coconut fibre contributes hydroxyl-rich, anisotropic fibrous reinforcement; and corncob ash contributes a rigid, siliceous particulate phase. No new reaction-specific absorption bands were observed, indicating that the constituents interact primarily through physical encapsulation, mechanical interlocking, dipolar attraction and hydrogen bonding rather than through confirmed covalent grafting. This distinction is important for interpreting the mechanical results in Sections Tensile strength - Flexural strength: rigid particles and fibres can restrict local deformation under

bending and indentation even without covalent bonding, explaining why hardness and flexural strength improved broadly across the composite series, whereas tensile loading is more sensitive to interfacial discontinuities, fibre ends and voids, explaining the corresponding reduction in tensile strength.

Table 2. Principal FTIR bands identified in the constituent materials and their implications for composite behaviour.

Material	Band (cm^{-1})	Assignment	Composite implication
PVC	3000-2850	Aliphatic C-H stretching	Polymer backbone; matrix continuity
PVC	1430-1330	CH_2 deformation/wagging	Confirms vinyl-chain structure
PVC	700-600	C-Cl stretching	Diagnostic PVC band; weakly polar matrix
Coconut fibre	3500-3200	O-H stretching	Hydrogen bonding and moisture affinity
Coconut fibre	1740-1700	C=O (hemicellulose/waxes)	Removable surface constituents
Coconut fibre	1600-1500	Aromatic lignin vibrations	Toughness and crack bridging
Coconut fibre	1250-1000	C-O-C/C-O (polysaccharides)	Cellulosic reinforcement signature
Corncob ash	1100-900	Si-O/Si-O-Si stretching	Rigid siliceous particulate phase
Corncob ash	<800	Silica bending/metal-oxygen	Mineral residue; hardness contribution

SEM Morphology and EDS Elemental Composition

1. SEM morphology

SEM examination of the fractured surface of the unreinforced PVC control (Figure 1) revealed a homogeneous, single-phase morphology dominated by coarse, stepped, laminar fracture terraces with directional striations radiating across the field of view, alongside a more compact, closely packed granular substructure in adjoining regions. This morphology is characteristic of brittle, cleavage-type crack propagation through a continuous glassy thermoplastic matrix, and the absence of any embedded particles, fibres, voids or interfacial gaps confirms that fracture in the control was governed solely by the cohesive strength of the PVC

phase rather than by the stress-concentrating defects that characterise the hybrid composites.

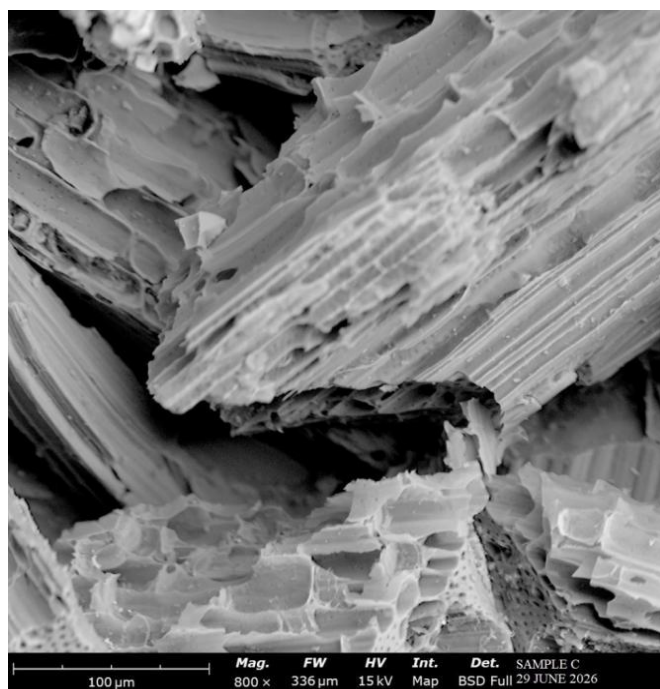


Figure 1. SEM micrograph of the unreinforced PVC control (800× magnification, FW 336 μm, 15 kV, backscattered-electron detector).

The tightly packed granular domains are consistent with well-fused PVC resin grains consolidated during compression moulding, indicating adequate matrix fusion in the absence of any reinforcement. This defect-sparse, single-phase microstructure provides a direct structural explanation for the markedly higher tensile strength recorded for the control (55.46 MPa) relative to every hybrid formulation (Section Tensile strength), and establishes the morphological baseline against which the fibre- and ash-induced heterogeneity of the reinforced composites C1, C3, C4, C6 and C9 is compared below.

By contrast, SEM examination of the fractured composite surfaces revealed a heterogeneous, multiphase morphology typical of short natural-fibre/particulate thermoplastic composites, with clear composition-dependent variation. C1 (Figure 2) shows a rough, densely textured surface in which numerous bright, high-backscatter-contrast particles – consistent with mineral ash – are unevenly distributed through a duller organic matrix, together with a fine filamentous strand consistent with an exposed coconut-fibre remnant and irregular dark cavities in the upper region consistent with incomplete wetting or fibre/particle pull-out. These features are consistent with the coexistence, in C1, of a near-maximum flexural strength with a markedly reduced tensile strength: fibres and particles embedded near the tensile bending surface can

bridge developing cracks, whereas the same cavities become critical stress concentrators under direct uniaxial tension.



Figure 2. SEM micrograph of C1 (3 wt.% coconut fibre, 3 wt.% corncob ash) (1000× magnification, FOV 269 μm, 15 kV, backscattered-electron detector).

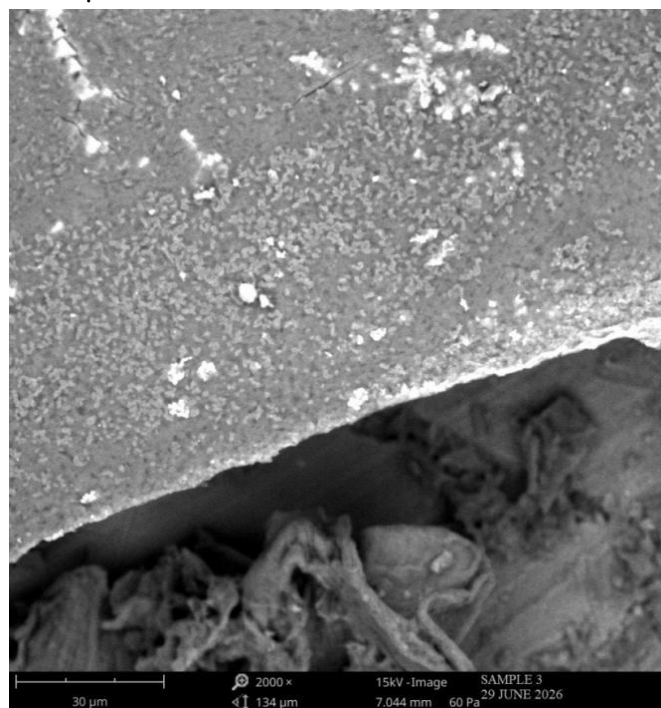


Figure 3. SEM micrograph of C3 (3 wt.% coconut fibre, 10 wt.% corncob ash) (2000× magnification, FOV 134 μm, 15 kV, low-vacuum, 60 Pa).

C3 (Figure 3) displays a comparatively continuous, finely textured matrix-rich region occupying the upper part of the field, containing sparse, finely dispersed bright particles, sharply separated by a diagonal fracture step from a rougher, folded, fibrous-looking region beneath. This relatively compact, well-consolidated upper zone is consistent with the comparatively high tensile strength recorded for C3 among the composites (Section Tensile strength) and with its correspondingly high compressive and thermal performance reported elsewhere in the wider study.



Figure 4. SEM micrograph of C4 (5 wt.% coconut fibre, 3 wt.% corncob ash) (500× magnification, FOV 537 µm, 15 kV, backscattered-electron detector).

C4 (Figure 4), which recorded the highest measured hardness of the entire series (Section Hardness), exhibited a densely packed, well-integrated morphology in which numerous small bright particles are distributed throughout an interlocked, polygonal matrix structure, together with an embedded fibrous strand and comparatively few large open cavities relative to the more fibre-rich formulations. This microstructure is consistent with a fibre-to-ash ratio that preserved sufficient PVC to bind the reinforcements while still constraining the near-surface region against indentation.

C6 (Figure 5) shows a broad, relatively smooth and featureless upper region containing fine, branching, high-backscatter-contrast mineral deposits and a fine surface crack, sharply separated by a fracture step from a rough, folded and locally separated zone beneath. This large, weakly bonded interfacial region offers a plausible microstructural explanation for the reduced tensile and

compressive performance recorded for C6 despite its comparatively high ash content and correspondingly high thermal residue.

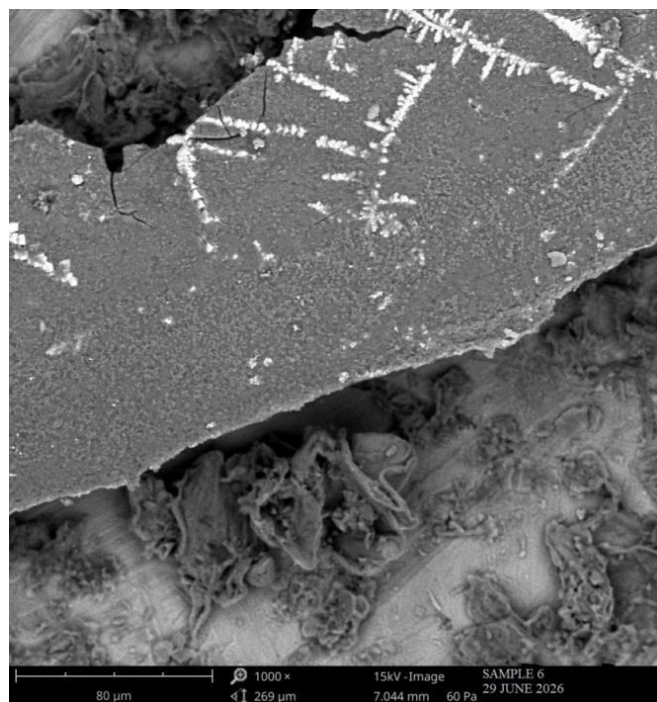


Figure 5. SEM micrograph of C6 (5 wt.% coconut fibre, 10 wt.% corncob ash) (1000× magnification, FOV 269 µm, 15 kV, low-vacuum, 60 Pa).



Figure 6. SEM micrograph of C9 (10 wt.% coconut fibre, 10 wt.% corncob ash) (500× magnification, FOV 537 µm, 15 kV, backscattered-electron detector).

C9 (Figure 6), the most heavily reinforced formulation, is highly heterogeneous and densely filled: numerous particles and elongated fibrous fragments are visible throughout, with extensive bright mineral specks and scattered dark cavities, leaving only limited regions of uninterrupted PVC. This quasi-continuous reinforcement skeleton is consistent with the exceptional flexural strength recorded for C9 (Section Flexural strength), but the associated high density of interfaces and probable microvoids also provides a structural explanation for its markedly elevated water absorption (Section Water absorption).

Taken together, these morphological observations are consistent with reports that coir-surface condition and fibre/matrix interaction govern the coherence of the resulting composite microstructure (Putra et al., 2020; Boussehel et al., 2024), and confirm, across the present formulation series, that composite quality is governed less by total reinforcement loading than by the extent to which PVC continuity and wetting are preserved around the fibre and particulate phases.

2. EDS elemental composition

Energy-dispersive X-ray spectroscopy (EDS) point/area analyses were acquired from the same fracture surfaces examined by SEM to provide qualitative, sample-level confirmation of the elemental constituents associated with the PVC matrix, coconut fibre and corncob ash phases. Across all six samples, the recurring detection of carbon (from PVC and coconut fibre) together with silicon, aluminium, iron, calcium, magnesium, sodium and potassium (consistent with corncob ash and with inorganic stabiliser/filler additives already present in the commercial PVC resin, Section XRD phase analysis) supports the hybrid organic-mineral character established by FTIR (Section FTIR spectral characterisation of the constituent materials) and XRD (Section XRD phase analysis). As with the parent characterisation dataset, the EDS acquisition records contain internal inconsistencies that restrict the analysis to a qualitative, comparative role rather than a strictly quantitative one: several rows show a mismatch between the tabulated atomic number and the reported element symbol or name – for example, the C1 dataset records a row as element 20 with symbol “Ca” but names it “Carbon” – and the EDS spectrum image supplied with the acquisition records is identical for the control, C6 and C9, and identical for C1 and C4, indicating that a single spectral file was associated with more than one specimen at the point of data collection. The figures and tables below are reproduced exactly as recorded, and are interpreted only in terms of the recurring, chemically plausible elements common to PVC, coconut fibre, corncob ash and typical PVC additive packages.

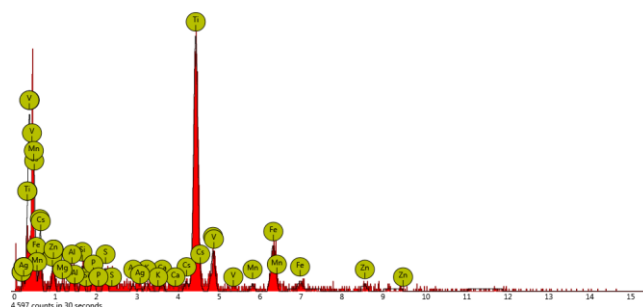


Figure 7. EDS spectrum recorded for the control.

Table 3. EDS elemental composition recorded for the control, as reported in the acquisition dataset.

Element No.	Symbol	Element name	Atomic conc. (%)	Weight conc. (%)
22	Ti	Titanium	2.23	2.91
26	Fe	Iron	12.64	0.22
30	Zn	Zinc	5.33	8.49
12	C	Carbon	33.32	36.02
11	Na	Sodium	7.22	3.29
47	Ag	Silver	9.12	2.28
25	Mn	Manganese	2.45	2.20
14	Si	Silicon	3.54	1.90
16	S	Sulfur	2.43	1.89
13	Al	Aluminium	13.10	11.81
23	V	Vanadium	1.26	1.19
15	P	Phosphorus	1.57	1.00
20	Ca	Calcium	1.20	0.94
12	Mg	Magnesium	1.30	0.87
19	K	Potassium	0.98	0.79

The control spectrum and table (Figure 7, Table 3) show carbon (36.02 wt.%) and aluminium (11.81 wt.%) as the dominant constituents, together with recurring signals from Fe, Zn, Na, Si, Mn, S, Ca, Mg, K, Ti and V, consistent with a formulated PVC compound containing stabiliser and filler additives rather than a chemically pure resin (Section XRD phase analysis).

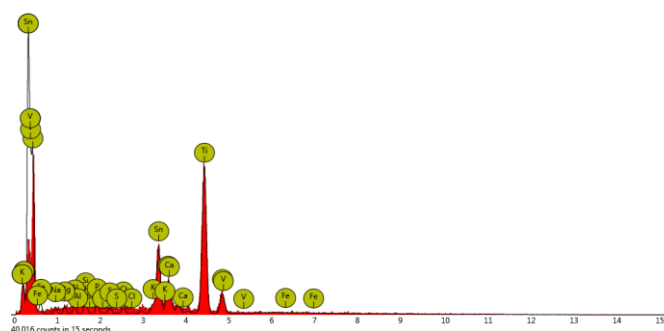


Figure 8. EDS spectrum recorded for C1.

For C1 (Figure 8, Table 4), silicon (22.54 at.%), sodium, magnesium, potassium and phosphorus are prominent alongside iron and chlorine, consistent with a mixed cellulosic/ash surface region; the anomalous

row recorded with symbol “Ca” but named “Carbon” (21.54 wt.%) most plausibly corresponds to a carbon-rich area of the fracture surface, given the otherwise limited standalone carbon signal in this particular dataset.

Table 4. EDS elemental composition recorded for C1, as reported in the acquisition dataset.

Element No.	Symbol	Element name	Atomic conc. (%)	Weight conc. (%)
22	Ti	Titanium	0.54	1.22
50	Sn	Tin	5.22	4.10
11	Na	Sodium	11.32	12.43
14	Si	Silicon	22.54	7.05
12	Mg	Magnesium	12.10	10.23
19	K	Potassium	10.22	11.34
15	P	Phosphorus	12.44	10.23
13	Al	Aluminium	6.34	1.96
17	Cl	Chlorine	4.91	1.43
20	Ca	Carbon (sic)	21.34	21.54
16	S	Sulfur	5.23	0.40
23	V	Vanadium	0.15	0.17
26	Fe	Iron	14.95	6.45

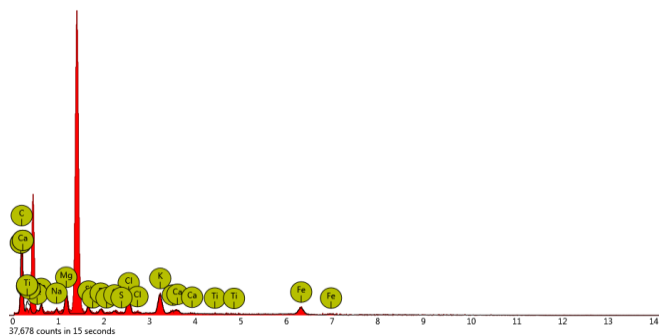


Figure 9. EDS spectrum recorded for C3.

Table 5. EDS elemental composition recorded for C3, as reported in the acquisition dataset.

Element No.	Symbol	Element name	Atomic conc. (%)	Weight conc. (%)
6	C	Carbon	37.97	32.46
7	N	Nitrogen	4.67	3.88
26	Fe	Iron	6.75	4.91
19	K	Potassium	2.63	6.63
12	Mg	Magnesium	2.34	4.12
17	Cl	Chlorine	5.35	6.23
20	Ca	Calcium	8.51	3.32
14	Si	Silicon	9.66	8.20
11	Na	Sodium	0.54	1.15
15	P	Phosphorus	0.28	0.56
16	S	Sulfur	10.28	19.58
16	O	Oxygen	12.10	15.20

The C3 spectrum and table (Figure 9, Table 5) are dominated by carbon (32.46 wt.%) and sulfur (19.58

wt.%), with oxygen, silicon, calcium, chlorine, iron and potassium also recorded, broadly consistent with a matrix-rich region containing a dispersed siliceous/mineral fraction, in agreement with the comparatively continuous morphology observed by SEM (Figure 3).

C4 (Figure 10, Table 6) shows a similar elemental profile to C1, again dominated by silicon, sodium, magnesium, potassium, phosphorus, carbon (31.54 wt.%) and iron, consistent with the densely packed, well-dispersed mineral-particle morphology observed by SEM (Figure 4) and with its correspondingly high hardness (Section Hardness).

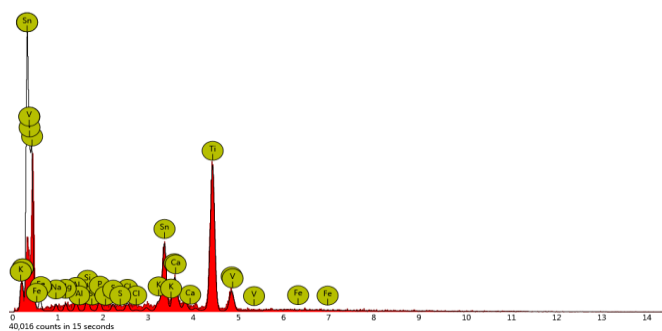


Figure 10. EDS spectrum recorded for C4

Table 6. EDS elemental composition recorded for C4, as reported in the acquisition dataset.

Element No.	Symbol	Element name	Atomic conc. (%)	Weight conc. (%)
22	Ti	Titanium	2.54	1.22
50	Sn	Tin	5.22	4.10
11	Na	Sodium	11.32	12.43
14	Si	Silicon	10.54	7.05
12	Mg	Magnesium	12.10	10.23
19	K	Potassium	10.22	11.34
15	P	Phosphorus	12.02	10.56
13	Al	Aluminium	6.34	1.96
17	Cl	Chlorine	4.91	1.43
12	C	Carbon	31.34	31.54
16	S	Sulfur	5.23	0.40
23	V	Vanadium	0.15	0.17
26	Fe	Iron	14.95	6.45

For C6 (Figure 11, Table 7), carbon (46.02 wt.%) and silver (32.34 wt.%) dominate the weight-percentage data, alongside iron, silicon, manganese, sodium, aluminium and titanium. The very high reported silver content should be treated cautiously in the absence of a plausible silver source in this formulation, but the co-occurrence of carbon, iron, silicon and aluminium is consistent with the mixed organic/mineral surface observed by SEM (Figure 5).

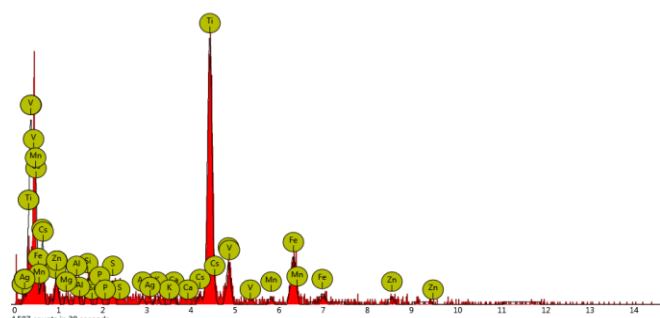


Figure 11. EDS spectrum recorded for C6

Table 7. EDS elemental composition recorded for C6, as reported in the acquisition dataset.

Element No.	Symbol	Element name	Atomic conc. (%)	Weight conc. (%)
22	Ti	Titanium	2.11	2.91
26	Fe	Iron	17.05	10.22
30	Zn	Zinc	2.02	8.49
12	C	Carbon	22.11	46.02
11	Na	Sodium	6.95	3.19
47	Ag	Silver	31.43	32.34
25	Mn	Manganese	4.45	2.19
14	Si	Silicon	7.22	1.30
16	S	Sulfur	3.65	1.20
13	Al	Aluminium	3.54	1.30
23	V	Vanadium	1.10	1.20
15	P	Phosphorus	1.34	1.34
20	Ca	Calcium	1.54	0.94
12	Mg	Magnesium	1.43	0.45
19	K	Potassium	0.23	0.43

The C9 spectrum and table (Figure 12, Table 8) again show carbon (36.32 wt.%) as dominant, together with iron, zinc, silver, silicon, aluminium and sodium, consistent with the highly heterogeneous, densely filled morphology observed by SEM (Figure 6) and with the persistent mineral phases confirmed by XRD for this formulation (Section XRD phase analysis). Taken together, the EDS results corroborate the SEM and XRD evidence that all formulations contain a carbon-dominated organic phase (PVC and coconut fibre) together with a recurring set of inorganic elements – principally Si, Al, Fe, Ca, Mg, Na and K – attributable to corncob ash and to stabiliser/filler additives already present in the commercial PVC resin. The comparatively large and formulation-dependent signals for Fe, Zn, Ag, Sn, Ti and V are consistent with a heterogeneous distribution of trace mineral and additive phases rather than with any deliberate alloying, and should be confirmed by more targeted, sample-specific EDS acquisition before being used for quantitative compositional claims. Within these limits, the elemental data support the same structure-property picture developed from SEM and XRD: formulations with a

more continuous, better-dispersed elemental distribution (C3, C4) correspond with improved tensile and compressive performance, while the most heterogeneous elemental and morphological pattern (C9) corresponds with the highest flexural strength and the highest water absorption.

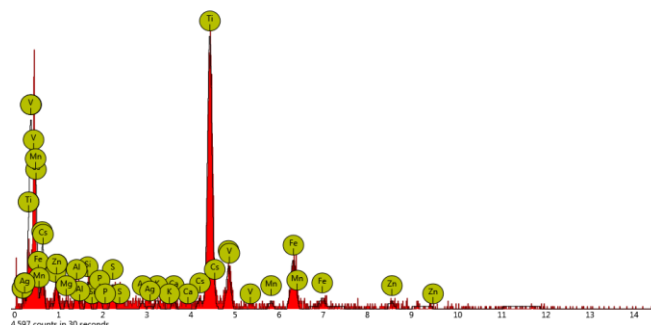


Figure 12. EDS spectrum recorded for C9

Table 8. EDS elemental composition recorded for C9, as reported in the acquisition dataset.

Element No.	Symbol	Element name	Atomic conc. (%)	Weight conc. (%)
22	Ti	Titanium	2.11	2.91
26	Fe	Iron	17.65	10.32
30	Zn	Zinc	6.22	8.54
12	C	Carbon	30.22	36.32
11	Na	Sodium	12.22	3.54
47	Ag	Silver	3.54	2.28
25	Mn	Manganese	1.34	2.54
14	Si	Silicon	3.10	1.43
16	S	Sulfur	2.43	1.65
13	Al	Aluminium	3.43	1.34
23	V	Vanadium	1.10	1.54
15	P	Phosphorus	1.32	1.23
20	Ca	Calcium	2.43	0.54
12	Mg	Magnesium	1.20	0.654
19	K	Potassium	0.43	0.32

XRD phase analysis

XRD patterns of the control and selected composites (Table 9) exhibited a dominant reflection at approximately $27-28^\circ 2\theta$, together with several lower-intensity peaks across the scanned range. Reference-pattern matching identified quartz or quartz-like phases in most samples, together with candidate graphitic, iron-bearing and oxide phases. The strong quartz-related reflection is consistent with the siliceous character of corncob ash established by FTIR (Section *Corncob ash*), while the weaker graphitic contribution likely reflects carbonaceous material or automated matching against the broad polymer/char background. Notably, the unreinforced PVC control also displayed mineral reflections, indicating that the commercial PVC resin was itself a formulated compound containing stabiliser,

pigment or filler phases rather than a chemically pure polymer; this observation is important for interpreting phase and elemental data, since some inorganic signals in the composites may originate partly from PVC additives rather than exclusively from the corncob ash. The high-ash formulations C3, C6 and C9 exhibited persistent, sharp mineral peaks, consistent with their comparatively higher ash content and providing structural support for the mineral-driven improvement in hardness (Section Hardness). C4 likewise exhibited a strong mineral signature despite its lower total reinforcement content, indicating that a moderate but well-dispersed crystalline filler fraction, consistent with the compact SEM morphology described in Section SEM morphology, can be mechanically more effective than a larger but poorly dispersed quantity. Taken together, the XRD and SEM evidence establish a coherent structure-property picture: crystalline mineral particles increase hardness, while heterogeneous interfaces and voids reduce tensile performance and increase water uptake, in agreement with the broader literature on hybrid mineral/fibre reinforcement of thermoplastics (Mulana et al., 2024; Sathiparan, 2025).

Table 9. Summary interpretation of the XRD patterns of the control and selected composites.

Sample	Principal observed/candidate features	Structure-property implication
Control	Strong reflection near 27-28°; quartz/graphitic and oxide matches	PVC compound contains crystalline mineral additives
C1	Quartz/graphitic peaks with minor goethite-type matches	Low loading introduces identifiable ash-related reflections
C3	Quartz-rich dominant peak; minor candidate phases	High ash content increases crystalline inorganic contribution
C4	Dominant quartz-like peak with minor candidate phases	Compact mineral-polymer structure; consistent with high hardness
C6	Quartz-related dominant reflection; low-intensity peaks	High ash fraction increases crystalline-phase persistence
C9	Strong quartz-related reflection; multiple minor candidates	Highest reinforcement gives most pronounced mineral signature

Tensile strength

The unreinforced PVC control recorded the highest tensile strength of the entire study, 55.46 MPa (Table 10). All nine hybrid formulations exhibited lower tensile strength, ranging from 19.27 MPa (C8) to 36.89 MPa (C5), corresponding to reductions relative to the control of between 33.5% (C5) and 65.3% (C8). This outcome shows

that, in its present unmodified form, the coconut fibre/corncob ash hybrid system did not improve the ultimate tensile strength of PVC, even though several formulations substantially improved other properties (Sections Hardness - Flexural strength). The reduction is attributable to four interlinked mechanisms established by the FTIR and SEM evidence above: interruption of the continuous PVC phase that alone carries the full tensile load in the control; the intrinsic polarity mismatch between the hydroxyl-rich fibre surface and the weakly polar PVC backbone, which can precede fibre rupture through interfacial debonding; stress concentration at ash agglomerates and poorly wetted fibre bundles; and voids generated during compression moulding of the high-viscosity PVC compound, which coalesce into cracks under axial tension. Among the composites, C5 (5 wt.% fibre, 5 wt.% ash) recorded the highest tensile strength, followed by C4 (32.09 MPa) and C9 (32.03 MPa); the lowest values occurred at high fibre loading combined with low ash content (C7, C8), suggesting that 10 wt.% fibre generated a high density of fibre ends and interfaces that 3-5 wt.% ash could not adequately stabilise. The non-monotonic trend at fixed fibre loading – for example, tensile strength rising from 23.83 MPa in C1 to 30.94 MPa in C3 as ash increased from 3 to 10 wt.% at a constant 3 wt.% fibre – indicates an interior packing optimum rather than a simple loading-dependent decline.

This behaviour does not imply that coconut fibre is intrinsically weak as a PVC reinforcement: Oladele et al. (2022) reported improved tensile performance in related PVC-coconut fibre-corn-cob ash systems under favourable processing and higher coconut-fibre fractions, while Putra et al. (2020) and Boussehel et al. (2024) demonstrated that fibre-surface treatment can directly improve fibre-matrix interfacial adhesion and mechanical performance in comparable natural-fibre/PVC systems. The present results therefore identify interfacial quality, dispersion and fibre-ash balance, rather than the reinforcement concept itself, as the principal levers for future tensile improvement.

Hardness

Hardness increased in every reinforced formulation relative to the unreinforced control value of 19.60 HV (Table 10), confirming that both reinforcements restricted local plastic deformation under indentation. The increase was modest in C1 and C2 (22.24 and 23.60 HV) but reached a maximum of 34.54 HV in C4 (5 wt.% fibre, 3 wt.% ash), a 76.2% improvement over neat PVC. C9, C8 and C3 also showed strong gains of approximately 62.4%, 58.8% and 45.8%, respectively. The rigid mineral phases confirmed by XRD (Section XRD phase analysis) resist indentation and reduce the volume of deformable polymer beneath the indenter,

while well-anchored coconut fibre additionally contributes stiffness where fibres are oriented across the indentation zone. The particularly high hardness of C4 is consistent with the compact, well-bonded near-surface structure observed by SEM: its comparatively low total reinforcement content (8 wt.%) preserved sufficient PVC to encapsulate the solid phases while the reinforcement itself constrained yielding. The response was non-monotonic with respect to ash content at fixed fibre loading. At 5 wt.% fibre, hardness fell from 34.54 HV in C4 to 26.56 HV in C5 and 25.22 HV in C6 as ash rose from 3 to 10 wt.%, suggesting that excess ash at this fibre level promoted particle clustering or void formation that reduced near-surface resistance. Conversely, at 10 wt.% fibre, hardness rose from 24.48 HV (C7) to 31.84 HV (C9) as ash increased, indicating that additional ash filled inter-fibre spaces and produced a more rigid skeleton once fibre content was already high.

These trends are consistent with reports that natural fibres combined with mineral or biomass-derived particulates increase hardness by restricting matrix chain mobility: Obada et al. (2020) reported enhanced rigidity in coir/coconut-husk particulate polymer composites, Ratanawilai and Raksarak (2024) found favourable hardness in coconut-fibre-reinforced recycled-polypropylene composites relative to other plant-fibre systems, and Oladele et al. (2022) similarly reported high hardness in coconut-fibre-containing PVC hybrids under favourable reinforcement distribution. Because hardness governs indentation and scratch resistance and dimensional retention at contact points, C4 emerges as the strongest experimental candidate for surfaces subject to repeated light contact.

Flexural strength

Flexural strength was the property most strongly and consistently improved by hybrid reinforcement (Table 10). The unreinforced control recorded only 13.22 MPa, whereas every composite formulation exceeded 19.60 MPa. The highest value, 41.79 MPa, occurred in C9 (10 wt.% fibre, 10 wt.% ash), a 216.1% increase over neat PVC; C1 (6 wt.% total reinforcement) was almost equivalent at 41.44 MPa, followed by C8 (35.08 MPa) and C6 (34.15 MPa). Even the lowest-performing composite, C7 (19.60 MPa), remained approximately 48.3% above the control. This improvement reflects the favourable mechanics of bending relative to direct tension. In three-point flexure, one surface experiences tension, the opposite surface compression, and the mid-plane shear; because the highest stresses occur at the outer surfaces rather than uniformly through the cross-section, fibres located near the tensile face can bridge developing cracks and delay propagation while ash particles and the PVC matrix support the compressive and shear components. A composite can therefore exhibit excellent flexural strength even when its bulk tensile strength is lower than that of the matrix, exactly as observed here. The occurrence of two local maxima, at the low-reinforcement C1 and the high-reinforcement C9, indicates that different microstructural routes can produce high bending resistance: C1 benefits from good PVC continuity around well-separated reinforcement, whereas C9 benefits from a dense, quasi-continuous hybrid skeleton. The intermediate formulations C2-C5 produced a plateau near 21-22 MPa, suggesting that neither mechanism was fully developed in that compositional region, while C6 and C8 regained high flexural strength once 10 wt.% ash or 10 wt.% fibre increased reinforcement continuity.

Table 10. Tensile strength, hardness and flexural strength of the control and hybrid composites, with percentage change relative to the control.

Sample	Tensile (MPa)	Δ Tensile (%)	Hardness (HV)	Δ Hardness (%)	Flexural (MPa)	Δ Flexural (%)
Control	55.46	—	19.60	—	13.22	—
C1	23.83	-57.0	22.24	+13.5	41.44	+213.4
C2	26.64	-52.0	23.60	+20.4	21.71	+64.2
C3	30.94	-44.2	28.58	+45.8	21.52	+62.8
C4	32.09	-42.1	34.54	+76.2	21.55	+63.0
C5	36.89	-33.5	26.56	+35.5	22.11	+67.2
C6	24.93	-55.0	25.22	+28.7	34.15	+158.3
C7	20.59	-62.9	24.48	+24.9	19.60	+48.3
C8	19.27	-65.3	31.12	+58.8	35.08	+165.3
C9	32.03	-42.3	31.84	+62.4	41.79	+216.1

These results parallel other hybrid natural-fibre composite systems: Oladele et al. (2022) reported improved flexural performance from combined coconut fibre and corncob ash reinforcement in PVC, with the optimum dependent on the fibre-to-ash balance; Kumar et al. (2023) reported improved mechanical and thermal

performance in coir-based hybrid composites through complementary load-carrying reinforcement functions; and Wasti et al. (2024) demonstrated that coir-containing thermoplastic hybrids can achieve useful bending performance when fibre architecture and consolidation are well controlled. For low-load components that

experience predominantly bending rather than direct tensile loading, these results are the most technically promising of the properties examined, and directly motivate treating flexural strength as a primary maximisation objective in the optimisation discussed in Section Multi-response optimisation of composite formulation.

Water absorption

Water absorption increased from 0.60% in the unreinforced control to between 0.99% (C1) and 1.90% (C9) across the hybrid series (Table 11), a trend broadly monotonic with total reinforcement loading. C9 recorded the highest value, corresponding to a 216.7% increase over the control, while C1 recorded the lowest composite value at 0.99% (+65.0%). The increase is attributable primarily to coconut fibre: the hydroxyl-rich cellulose and hemicellulose confirmed by FTIR attract water molecules through hydrogen bonding, while capillary pathways form along fibre lumens and fibre/matrix gaps, consistent with the pull-out cavities observed by SEM. Corncob ash contributed a smaller, secondary effect: at a constant 3 wt.% fibre, raising ash from 3 to 10 wt.% increased water absorption from 0.99% to 1.34%; at 5 wt.% fibre, from 1.15% to 1.50%; and at 10 wt.% fibre, from 1.55% to 1.90%.

Table 11. Water absorption of the control and hybrid composites.

Sample	Water absorption (%)	Δ vs. control (%)
Control	0.60	0.0
C1	0.99	+65.0
C2	1.09	+81.7
C3	1.34	+123.3
C4	1.15	+91.7
C5	1.25	+108.3
C6	1.50	+150.0
C7	1.55	+158.3
C8	1.65	+175.0
C9	1.90	+216.7

This consistent progression indicates that ash addition increased accessible pathways, or reduced the volume of impermeable PVC, in addition to the dominant fibre-driven effect. Even at its highest value, composite water absorption remained below 2%, a relatively low figure for many untreated natural-fibre thermoplastic composites and evidence that compression moulding achieved substantial reinforcement encapsulation. For context, Wasti et al. (2024) reported considerably higher water uptake at elevated coir contents in polypropylene hybrids, while Li et al. (2022) observed that water absorption in PVC/wood composites depended strongly on filler content and matrix coverage; the comparatively low

absolute values obtained here indicate the material's suitability for indoor and intermittently humid service, although long-term immersion and cyclic-humidity behaviour were not evaluated. This property has the most direct bearing on the optimisation discussed next: water absorption penalises the high-loading C9 formulation despite its outstanding flexural and hardness performance, and is therefore treated as a minimisation objective in the multi-response optimisation.

Multi-response optimisation of composite formulation

1. Optimisation criteria and Cox response trace

Because no single experimental formulation dominated all three properties of engineering interest (C5 excelled in tension but performed unremarkably elsewhere, C4 gave the best hardness, and C9 gave the best flexural strength but the worst water absorption), a multi-response, mixture-design optimisation was carried out using flexural strength and hardness as maximisation objectives and water absorption as a minimisation objective, each assigned equal weight and importance (Table 12). Individual desirabilities ranged from 0 (unacceptable) to 1 (target achieved) and were combined geometrically into a single composite desirability, such that a very poor result on any one response could substantially reduce the overall score irrespective of the other two. The Cox response trace plots, generated by fitting a mixture polynomial model to the experimental data and tracing each response as one component was varied proportionally relative to the design centroid, provided a mechanistic visualisation of the trade-offs identified qualitatively in Sections. For flexural strength, the coconut-fibre and corncob-ash traces both curved upward with similar magnitude near the reference blend, while increasing PVC reduced the predicted response, consistent with every reinforced composite outperforming the control in bending. For hardness, coconut fibre showed the strongest curvature, with a predicted maximum near a small positive deviation from the reference composition, while the ash response was flatter but still non-linear and increasing PVC again reduced predicted hardness. For water absorption, the trend reversed: increasing either coconut fibre or corncob ash raised predicted absorption while increasing PVC reduced it, with the fibre slope steeper than the ash slope, confirming coconut fibre as the dominant moisture-sensitive component. Collectively, the trace plots demonstrate that the optimum formulation must lie in the interior of the mixture space, balancing the mechanical gains of reinforcement against the accompanying moisture-uptake penalty.

Table 12. Multi-response optimisation criteria for the mixture-design desirability analysis.

Response	Goal	Lower	Target	Upper	Weight	Importance
Flexural strength (MPa)	Maximise	13.22	41.79	41.79	1	1
Hardness (HV)	Maximise	19.60	34.54	34.54	1	1
Water absorption (%)	Minimise	0.60	0.60	1.90	1	1

2. Global optimum and predicted responses

The desirability optimisation identified a global solution of 88.40 wt.% PVC, 5.95 wt.% coconut fibre and 5.66 wt.% corncob ash (precisely 88.398/5.945/5.657 wt.%), a composition close to the experimentally balanced C5 formulation but with marginally higher combined reinforcement (Table 13). This solution predicted a flexural strength of 32.14 MPa (desirability = 0.662), a hardness of 29.11 HV (desirability = 0.637) and a water absorption of 1.36% (desirability = 0.417), yielding a composite desirability of 0.560. The predicted flexural strength represents an approximately 143% improvement over the control, and the predicted hardness an approximately 48.5% improvement, while the predicted water absorption remains well below that of the high-loading formulations C6-C9. Water absorption was consistently the limiting response, and its comparatively low individual desirability (0.417) explains why the composite desirability, at 0.560, is moderate rather than close to unity: this outcome reflects a genuine, physically grounded conflict among the three objectives rather than a modelling artefact. The global solution should accordingly be interpreted as the best attainable compromise under equal response importance rather than the formulation that maximises every individual property; its predicted flexural strength exceeds that of C2, C3, C5 and C7, its predicted hardness exceeds that of C1, C2, C5, C6 and C7, and its predicted water absorption is lower than that of C6-C9, placing it in a genuinely favourable position across all three criteria simultaneously (Table 10, Table 11).

3. Alternative local solution and comparison

For comparison, an alternative local solution corresponding to the upper reinforcement boundary (10 wt.% coconut fibre, 10 wt.% corncob ash, 80 wt.% PVC, i.e., the C9 composition) was also evaluated (Table 13). This boundary solution predicted the highest flexural strength in the design space, 42.90 MPa, and a high hardness of 31.39 HV, but its predicted water absorption reached the upper experimental limit of 1.90%, giving a water-absorption desirability of zero and collapsing the composite desirability to approximately 0.000005 because the individual desirabilities are combined geometrically. This comparison illustrates,

quantitatively, why the boundary formulation is unsuitable as a general-purpose optimum despite its superior individual mechanical values: relative to the global solution, it sacrifices a 28.5% reduction in water absorption in exchange for approximately 25% additional predicted flexural strength, an unfavourable trade for products intended for even moderately humid indoor service. The result is consistent with the experimental evidence, where C9 combined the best measured flexural strength with the highest measured water absorption. The desirability-function approach therefore correctly excludes the mechanically strongest boundary composition from selection as the universal optimum, reinforcing the conclusion that formulation selection in this hybrid system must be treated as a genuinely multi-criteria decision rather than a single-property maximisation.

Table 13. Comparison of the global optimum and the alternative local (boundary) solution.

Parameter	Global solution	Local solution 2 (C9 boundary)
Coconut fibre (wt.%)	5.95	10.00
Corn cob ash (wt.%)	5.66	10.00
PVC (wt.%)	88.40	80.00
Predicted flexural strength (MPa)	32.14	42.90
Predicted hardness (HV)	29.11	31.39
Predicted water absorption (%)	1.36	1.90
Composite desirability	0.560	0.000005

4. Benchmarking against recent PVC- and polymer-based natural-filler composites

To contextualise the optimised formulation, its predicted responses were compared with recently published PVC- and polymer-based natural-filler composites (Table 14). The optimised flexural strength of 32.14 MPa is lower than the 37.55 MPa reported for a recycled-polypropylene/natural-fibre wood-species composite by Khamtree et al. (2024), the 41.3-45.3 MPa range reported for a flame-retardant beech-wood-flour/polypropylene composite by Boztoprak (2024), and the 43.5 MPa reported for a cassava-rhizome-powder/epoxy composite by Prasetsopha et al. (2025).

Table 14. Benchmarking of the optimised PVC hybrid composite against recent polymer-based natural-filler composites.

Study	System	Flexural (MPa)	Hardness	Water absorption (%)
Present study	PVC/5.95% coir/5.66% CCA (optimum)	32.14	29.11 HV	1.36
Khamtree et al. (2024)	Recycled PP/natural-fibre WPC	37.55 (max)	NR	5.59 (min, 8 wk)
Boztoprak (2024)	PP/beech-wood-flour WPC	41.3-45.3	75.8-81.0 Shore A	0.19-2.18
Prasoetsopha et al. (2025)	Epoxy/cassava-rhizome powder	43.5	76.2 Shore D	4.04
Nukala et al. (2022)	Recycled mixed-plastic/wood WPC	NR	7.21-19.72 HV	1.2-19.9
Afolabi et al. (2024)	Kenaf/glass sandwich composite	NR	29.267-49.800 (Barcol)	NR
Lewandowski et al. (2024)	Plasticised PVC/wood-flour	NR	NR	2.2-2.6 (840 h)

Note. NR = not reported as a directly comparable numerical value. Hardness values obtained on different scales (HV, Barcol, Shore A, Shore D) are not numerically interchangeable and are presented as reported.

This gap is technically reasonable: those studies employed different matrices, higher total reinforcement fractions, coupling agents or thermoset networks, whereas the present optimum retains only about 11.6 wt.% combined reinforcement and leaves PVC as the dominant continuous phase, representing a deliberately balanced, low-filler formulation rather than a maximum-stiffness one. The optimised hardness of 29.11 HV compares favourably with the recycled plastic/wood composite of Nukala et al. (2022), whose hardness increased from only 7.21 to a maximum of 19.72 HV with increasing wood content – the present value exceeds that maximum by approximately 47.6% – and is very close to the lower hardness value of 29.267 reported for a kenaf-face-sheet sandwich composite by Afolabi et al. (2024), although that study used a Barcol impresser and is not a direct Vickers-equivalent comparison. Water resistance is the strongest comparative attribute of the optimised composite: its predicted 1.36% water absorption is markedly lower than the 2.2-2.6% reported after 840 h immersion for plasticised PVC/wood composites by Lewandowski et al. (2024), the 4.04% reported for cassava-rhizome/epoxy composites by Prasoetsopha et al. (2025), and substantially below the 5.59% minimum reported after eight weeks for recycled-polypropylene wood-plastic composites by Khamtree et al. (2024).

5. Implications for sustainable, low-load applications

Taken together, the optimisation results indicate that the balanced global formulation offers a technically defensible combination of moderate bending resistance, moderate surface hardness and comparatively low moisture uptake, consistent with the FTIR, SEM and XRD evidence that a moderate, well-dispersed reinforcement fraction preserves matrix continuity while still delivering measurable reinforcement benefits. Its predicted water absorption of 1.36% is, in particular, well within the 8% mean water-absorption limit

specified for cladding profiles and tiles under EN 15534-5:2014 (European Committee for Standardization [CEN], 2014), providing a numerically favourable margin of approximately 83% relative to that limit, although formal compliance would require testing of the finished product under the standard's specified conditioning and exposure regime. The optimised formulation, and the underlying multi-response methodology, therefore support the use of coconut fibre and corncob ash as viable, sustainable reinforcements for non-load-bearing PVC composite applications, such as interior panels and cladding, where balanced bending resistance, surface durability and moisture tolerance are required simultaneously rather than any single property in isolation.

Conclusion

This study examined the tensile strength, hardness, flexural strength and water absorption of PVC composites hybrid-reinforced with coconut fibre and corncob ash, supported by FTIR, XRD and SEM characterisation, and used a mixture-design, desirability-function approach to identify a multi-response-optimised formulation for sustainable, low-load applications. FTIR confirmed a chemically distinct but physically compatible three-phase system: a weakly polar, C-Cl-rich PVC matrix, a hydroxyl-rich lignocellulosic coconut fibre, and a siliceous corncob ash. SEM and XRD linked well-wetted, matrix-continuous, mineral-rich microstructures to superior hardness and flexural performance, and linked fibre pull-out cavities and heterogeneous interfaces to reduced tensile strength and elevated water uptake. Reinforcement uniformly reduced tensile strength relative to neat PVC (55.46 MPa) to between 19.27 and 36.89 MPa, while increasing hardness (up to 34.54 HV, +76.2%) and flexural strength (up to 41.79 MPa, +216.1%) in every hybrid formulation, and increasing water absorption from 0.60% to at most

1.90%. Because no single formulation maximised all three of these properties simultaneously, a mixture-design optimisation that jointly maximised flexural strength and hardness while minimising water absorption was applied, identifying a global optimum of 88.40 wt.% PVC, 5.95 wt.% coconut fibre and 5.66 wt.% corncob ash, with predicted responses of 32.14 MPa flexural strength, 29.11 HV hardness and 1.36% water absorption (composite desirability = 0.560) — a substantially more balanced outcome than the mechanically strongest but moisture-compromised boundary formulation. Benchmarked against recent PVC- and polymer-based natural-filler composites, the optimised formulation offers comparatively low water absorption alongside moderate flexural and hardness performance, supporting its proposed use in non-load-bearing interior cladding and related low-load, waste-valorising PVC products. The results demonstrate that agricultural residues such as coconut husk and corncob can be converted into functional PVC reinforcements through a reproducible, multi-response optimisation framework, offering a scientifically grounded route toward more sustainable PVC-based composite materials. Future work should focus on interfacial treatment (for example, alkalisiation, silanisation or compatibiliser addition) to further improve tensile performance and reduce moisture sensitivity without sacrificing the flexural and hardness gains established in this study, and on validating the optimised formulation through finished-product testing.

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Author Contributions

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Conflicts of Interest

No conflict of interest.

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