UNIABUJA Journal of Engineering and Technology

https://ujet.uniabuja.edu.ng/
Special Issue

An Overview on Sustainable Additive Manufacturing from Recycled HDPE and Agricultural Waste Fibre Filaments

Kehinde L. OLAITAN[1], Adesewa S. SOMIDE[1], Abiodun Z. OLAITAN[2] and M Adekojo. WAHEED[1*]

[1]Department of Mechanical Engineering, Federal University of Agriculture Abeokuta, Nigeria.

[2]SGS Environmental Analytics, Steenhouwerstraat 15, 3194, Rotterdam, Netherlands.

olaitankl@funaab.edu.ng, somideadesewa@yahoo.com, abiodunzainabolaitan@gmail.com, *waheedma@funaab.edu.ng

Abstract

The increasing demand for 3D printing materials raises significant environmental concerns due to the widespread use of non-biodegradable polymers. This paper presents a systematic review of composite filaments developed from recycled high-density polyethylene (HDPE) reinforced with agricultural waste fibres for use in fused filament fabrication (FFF). A structured methodology was adopted, involving a literature search across peer-reviewed databases (2016–2026) using keywords such as "recycled HDPE filament," "agricultural fibre composites," and "FFF additive manufacturing," with studies selected based on relevance to filament fabrication, mechanical performance, and sustainability outcomes. Recycled HDPE is a promising matrix due to its mechanical durability and recyclability, though challenges such as shrinkage and warping during printing persist. To enhance its performance, various natural fibres, such as melon husk, banana fibre, and hemp are incorporated as reinforcements, leveraging their biodegradability, mechanical strength, and compatibility with polymer matrices. This review analyses filament fabrication techniques, including mechanical recycling, extrusion parameters, and the use of additives to improve fibre-matrix interaction. Performance evaluation methods such as Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR), and X-Ray Diffraction (XRD) are also discussed in assessing the composite's mechanical, structural, and thermal behaviour. Reviewed studies show that fibre reinforcement improves tensile strength, reduces warping, and enhances environmental degradability, though excessive fibre content may hinder printability. The integration of agricultural waste in recycled HDPE filaments presents a dual advantage: minimising plastic pollution and valorising agro-waste. The review concludes that agro-fibre-reinforced HDPE filaments hold significant promise for sustainable 3D printing, with further optimisation needed to balance fibre content, print quality, and mechanical performance for commercial applications.

Keywords: *Recycled HDPE, agricultural fibres, fused filament fabrication, sustainable composites, additive manufacturing.*

1 Introduction

1.1 Overview of 3D Printing and Material Requirements

From a process originally used to build rapid prototypes, additive manufacturing – better known as 3D printing – has grown into a truly revolutionary technology in its own right. From customised medical implants to advanced aerospace parts, 3D printing's ability to produce intricate and customisable designs from raw materials without waste has led it to displace traditional subtractive methods in production across several industries (Jeong et al., 2023). In medicine, 3D printing technologies have been utilised for producing patient-customised prosthetics, surgical instruments and tissue scaffolds for experimentation (Jeong et al., 2023). For engineering applications, the use of 3D printing has been able to significantly shorten product development times, due to the possibility to iterate between design and prototype phases (Kongre et al., 2023). 3D printing is compatible with polymers, metals, ceramics, and composites alike, which allows it to be utilised in any number of industries (Shahrubudin et al., 2019).

Received: 27-05-2026 / Accepted: 11-06-2026 / Published: 20-07-2026

https://doi.org/10.70118/ujet.2026.sp01.08

Unfortunately, the overwhelming prevalence of plastic filament materials in 3D printing poses significant risks to the environment. Traditional filament types are either petrochemical in origin, or produced in large quantities using high energy-intensive processes. More broadly, plastic pollution represents one of the most pressing environmental issues of the contemporary period, with plastics – being non-biodegradable and extremely persistent – accumulating in the soil, waterways, and oceans at unprecedented levels. Around 8.8 million tons of plastics leak into the world's oceans annually (Jambeck et al., 2015). An instructive example may be provided by Nigeria, where domestic plastic production grew from 353 to 523 kilotonnes between 2012 and 2022, but only around 12% of this material is actually recycled. Furthermore, in certain communities, waste plastics are deliberately released into waterways and lakes for the purposes of clearing lands. As a result of such practices, microplastics become concentrated in marine organisms via biomagnification and ultimately reach the human consumer (Sun et al., 2022; Idowu et al., 2024).

From the point of view of engineering applications, High Density Polyethylene (HDPE) stands out as one of the most promising candidates, due to its favourable mechanical properties. The high density of HDPE, its low melting temperature, excellent chemical resistance and high recycle rate all make it a strong prospect in FFF. However, the semi-crystalline nature of HDPE means that it shrinks and warps when it cools down after printing, which affects layer bonding and print quality (Dalloul et al., 2022; Atsani et al., 2024). Recycling HDPE further aggravates the issue, as repeated thermal treatments reduce its molecular weight and degree of crystallinity, lowering viscosity, impact resistance, and tensile strength (Ahmed et al., 2022; Xanthos et al., 2001).

One potential way to counteract those effects is by incorporating plant-derived fibres into the polymer matrix. Such natural fibres may be harvested from agriculture waste (such as melon husks), and their inclusion will help reinforce a printed part in addition to diverting waste products away from landfills and water bodies. Indeed, the idea of using plant-based waste to create stronger composites by recycling them into a thermoplastic matrix is increasingly being explored both academically and commercially. This paper is intended as a survey of the current state of knowledge regarding composite filaments made of recycled HDPE reinforced with agricultural waste fibres for FFF.

1.2 Motivation for Using Recycled HDPE and Agricultural Fibres

Due to the increasing environmental pressure caused by plastics, there is an increasing need to find suitable alternative materials and reinforcements for plastic-based materials. The possibility of using recycled high-density polyethylene (HDPE), which is one of the most frequently recycled plastics due to its strength and easy processability, as a basic material to create 3D printing filament is a promising choice. Although recycling can be seen as an attempt to solve plastic problems, there are technical limitations. Recycling processes cause the occurrence of thermomechanical degradation of recycled plastics, leading to decreased viscosities, impact toughness, and other mechanical properties (Ahmed et al., 2022; Xanthos et al., 2001).

Due to the decrease in mechanical properties caused by the thermomechanical degradation, agricultural fibres have been increasingly incorporated into recycled plastics as reinforcing materials (Ahmed et al., 2022; Xanthos et al., 2001). Agricultural fibres come from agro-industrial wastes, including crop residue or fruit peels. The usage of agricultural fibres as reinforcement materials helps increase mechanical performance and promotes circularity since agriculture residues are easily accessible resources (Xanthopoulou et al., 2023; Dalloul et al., 2022). Therefore, this review examines the combination of recycled HDPE and agricultural fibres in the production of filament for 3D printers.

1.3 Recycled HDPE as a Matrix for 3D Printing Filaments

Recycled HDPE has been successfully used as a matrix material for composite 3D printing filaments. Its compatibility with both synthetic and natural fibre reinforcements makes it versatile. For instance, Rubiano-Navarrete *et al.,* (2024) demonstrated that reinforcing HDPE with short banana fibres enhanced tensile strength, while Xanthopoulou *et al.,* (2023) confirmed the feasibility of using hemp fibre in HDPE composites for filament production and others.

Using HDPE as a matrix in fibre-reinforced filaments not only helps reduce environmental pollution but also provides a secondary application for plastic waste. Furthermore, Beg *et al.,* (2024) and Arantes *et al.,* (2018) emphasised that even after multiple recycling steps, fibre-reinforced HDPE can retain acceptable mechanical

https://doi.org/10.70118/ujet.2026.sp01.08

properties suitable for functional components in additive manufacturing. Other plastics alongside HDPE have also been used to produce 3D printing filaments.

1.4 Recycling Methods

HDPE can be recycled via mechanical or chemical processes. Mechanical recycling involves mechanical treatment of the waste materials through physical actions like grinding, washing, and melting without changing the structure of the polymer (Ahmed et al., 2022). Although economic, this technique does have the disadvantage of lowering the molecular weight and crystallinity of the recycled material, hence lowering its mechanical performance (Xanthos et al., 2001). On the other hand, chemical recycling involves breaking down of polymers through the process of depolymerisation into monomers or other basic chemicals. Unlike mechanical recycling, this technique results in high-quality end-products (Ahmad et al., 2023). However, this technique has not been commercialised because it requires higher energy consumption. When it comes to filament production, the mechanical recycling technique is favoured because of its simplicity and ability to be performed on small scales. Such examples include experiments done by Ingale et al., (2023), and Mohammed et al., (2017). Thermally induced degradations are some of the most critical problems facing the process of recycling of HDPE. As mentioned above, exposure to high levels of heat and shears during the process of extrusion tends to reduce the melt flow properties, tensile strength, and impact resistance of recycled plastics (Ahmed et al., 2022). These degradations cause poor adhesion between layers and surface finishes of the 3D printed material. Further complications arise from warping and shrinkage due to the semi-crystalline nature of the material (Tan et al., 2023). Addition of different compounds such as fiber reinforcement (melon husk or hemp) can improve the properties of HDPE by creating better interfacial bonding (Xanthopoulou et al., 2023; Dalloul et al., 2022).

2 Performance of Recycled HDPE in Extrusion and Printing

Several experiments have confirmed that recycled HDPE can be successfully converted into printable filament, although printability often depends on precise extrusion parameters. Atsani *et al.,* (2024) found that the addition of glass powder to recycled HDPE improved viscosity and printability, while Dalloul *et al.,* (2022) observed reduced warpage in HDPE composites with modified cellulose nanofibrils. Similarly, Gunesegeran *et al.,* (2022) reported strong mechanical properties and water resistance in HDPE-based tiles, indicating that careful processing can yield high-performance results. However, Ferrari *et al.,* (2020) and Little *et al.,* (2020) highlighted that multiple extrusion cycles could degrade crystalline structure, impacting final product consistency. Further, studies have demonstrated that recycled HDPE, when processed correctly, can produce filaments suitable for use in Fused Filament Fabrication (FFF) 3D printing. For example, Cunico *et al.,* (2019) evaluated the post-processing potential of FDM parts made from recycled polymers, showing improvements in surface finish and structural integrity after coating. Performance testing using SEM, FTIR, and XRD techniques is critical in evaluating the printability and structural quality of recycled HDPE filaments (Polline *et al.,* 2021). Such tests help identify flaws such as voids, poor fibre dispersion, or thermal stress, guiding necessary process modifications.

2.1 Processing techniques for filament fabrication

According to Ahmad et al., (2023) study review, consistency in filament diameter (approximately 1.75 ± 0.05 mm) is essential since inconsistency in size could lead to under/over-extrusion while printing. The extrusion machines vary from single screw to twin-screw models. Different extrusion machines determine the dispersion and melting characteristics and surface quality of the filament produced. In order to produce filaments from recycled polymers, the mechanical processing of waste plastics into flake form or pellets needs to take place. As per Nikam et al., (2023), after cleaning and drying, PET plastic bottles were mechanically processed into strips, then melted and extruded into filaments with diameter 1.65 mm through FLAbot extruder system. The same procedure is applied for HDPE with the necessary modification of temperature since it melts easily owing to its relatively low thermal resistance.

Agricultural fibres need special processing to ensure high compatibility with the polymer matrix. This process enables the production of filaments with homogenous dispersion in HDPE and minimises nozzle clogging in the course of 3D printing. Inconsistency in size of agricultural fibres leads to non-homogeneity in the filament and low strength of products manufactured on 3D printers. For instance, according to Tan et al., (2023), disposable chopsticks needed to be treated with alkali solution (1 mol NaOH) to remove any substances on their surface like wax, hemicellulose, and lignin. Such a pretreatment increases compatibility with the polymer matrix. Fibres were

https://doi.org/10.70118/ujet.2026.sp01.08

dried at 80 °C up to 24 hours until reaching a stable weight and moisture removal. The following step included crushing the fibres into particles of 250 µm, thus making them ready for compounding with thermoplastics like.

2.2 Extrusion parameters for filament production

Table 1 presents a comparative overview of studies that explore different extrusion systems and their effectiveness in producing filaments from recycled high-density polyethylene (HDPE), either as standalone material or reinforced with natural fibres. These studies reflect significant developments in low-cost, sustainable filament production, highlighting a variety of extruder configurations, operational parameters, and printability outcomes. Each entry contributes uniquely to our understanding of the mechanical, structural, and practical implications of using recycled materials in 3D printing.

2.2.1 Extruder Design and Screw Configuration

The majority of the studies that were reviewed in this work used single screw extruders, which were popular in use due to ease-of-use, relatively affordable pricing, and simple control methods. For example, Arendra et al. (2019) relied on a single screw that can be controlled in terms of rotational speed to study the effects of temperature and screw speed on the uniformity of filaments. While no printing trials were performed, the research provided a foundation of knowledge on how different process parameters may impact filament geometries. Sonjaya et al. (2020; 2021) also relied on customized single-screw extruders combined with PID controllers to enhance temperature stabilization and extrusion consistency, thus facilitating the production of filament materials with relatively good quality in terms of both surface finish and overall stability, especially when reinforced by natural fibres such as coconut. The use of locally-designed equipment such as that used by Ogbonnaya et al. (2024) and Ademoroti (2024) is reflective of current trends in FDM technology. The main purpose of those devices was to enable the recycling of HDPE and fiber-reinforced materials, but certain restrictions regarding spooling, extrusion rate, and mechanical properties remained.

2.2.2 Filament Diameter and Dimensional Consistency

Achieving a consistent filament diameter is crucial for 3D printing performance, especially for fused deposition modelling (FDM) systems that rely on standard diameters such as 1.75 mm ± 0.05 mm. Most researchers aimed for this target, with varying degrees of success. Ingale *et al.* (2023) confirmed their filament met this diameter specification and demonstrated successful printing with minimal warping. On the other hand, Woern *et al.* (2018) reported a ±4.6% variation using a Recyclebot, which could pose challenges in real-world printing, especially for parts requiring high dimensional precision. Arendra *et al.* (2019) specifically evaluated filament roundness and uniformity, finding a direct correlation with extrusion temperature and screw speed. Such findings reinforce the importance of tight process control during extrusion. Despite not testing printability, this work provides insights that are highly applicable to quality assurance in filament fabrication.

2.2.3 Printability and 3D Printing Performance

Printability is the ultimate test of filament quality. Studies like those by Sonjaya *et al.* (2021) and Ogbonnaya *et al.* (2024) not only extruded filaments but also successfully printed with them, using standard FDM printers such as the Delta 3D Printer and FlashForge Finder Lite. These works reported good bed adhesion and minimal warping, although issues such as slight diameter variation and reduced performance at higher fibre loadings were also observed. Nozzle clogging, especially with high fibre content—is a recurring limitation in natural fibre-reinforced HDPE composites, as seen in Sonjaya *et al.* (2020). Setiawan *et al*. (2021) introduced an innovative pellet-fed FDM system that bypassed the need for filament spooling. Their PID-controlled setup demonstrated successful real-time printing from HDPE pellets. While this approach eliminates filament winding issues, it is not directly applicable to standard FDM systems and limits material handling flexibility. Nonetheless, this technique could prove useful in industrial or high-throughput environments where in-line extrusion is viable.

https://doi.org/10.70118/ujet.2026.sp01.08

Table 1: **Comparative overview of studies that explore different extrusion systems and their effectiveness in producing filaments from recycled high-density polyethylene (HDPE),**

S/N	Author	Type of Extruder	Screw type	Filament Diameter	Printability	3D Printer	Operating Temp.	Research Contribution	Limitations
1	Arendra *et al*. (2019)	Filament extruder	Single screw with speed control (stepper motor)	2 mm (targeted), roundness and uniformity analyzed	Not explicitly evaluated; focus was on extrusion quality	Not specified	180 °C, 200 °C, 220 °C (tested)	Developed low-cost HDPE filament extruder; established relationship between temperature, screw speed, and filament geometry	Printability not tested; actual filament output performance in printing not assessed
2	Setiawan *et al*. (2021)	FDM with pellet-fed extruder	Stepper motor-driven screw	2 mm extrusion, not spooled filament	Direct extrusion (not filament spooling); print success dependent on PID controller	CNC-driven FDM printer with 3DOF	200 °C	Demonstrated PID-controlled HDPE extrusion from pellets directly into 3D printed forms	Not applicable for filament production; process optimized only for real-time extrusion
3	Sonjaya *et al*. (2020)	Single screw extruder	Custom single screw	1.75 mm (targeted)	Good printability with appropriate nozzle and bed temperature	Delta 3D Printer	200 - 240 °C	Examined effects of fibre loading on recycled HDPE filament printability	Printability decreased with high fibre content; nozzle clogging observed
4	Sonjaya *et al*. (2021)	Single screw extruder	Custom screw with PID control	1.75 mm	Filament successfully used in printing with minimal warping	Delta FDM printer	220 °C (nozzle), 70 °C (bed)	Demonstrated use of coconut fibre in recycled HDPE filaments	Slight variations in filament diameter and bed adhesion issues
5	Woern *et al.* (2018)	RepRapable Recyclebot	Single screw, 5/800 configuration	1.75 mm (± 4.6%)	Designed for filament production; printing not	Compatible with RepRap systems (e.g., Lulzbot Taz)	<250 °C for most thermoplast	Developed open-source recyclebot capable of producing filament from waste	System performance with composite or contaminated

https://doi.org/10.70118/ujet.2026.sp01.08

					tested in this study				feedstocks not fully explored
6	Ingale *et al.* (2023)	Single screw extruder	Single screw (with heating zones)	1.75 mm (confirmed for 3D printing)	Printed successfully with minimal warping	3D printer with 0.4 mm nozzle (likely FDM)	220 °C (print), 80 °C (bed)	Demonstrated banana fiber-reinforced HDPE filaments from waste using 3D printing	No standard mechanical testing beyond visual and dimensional checks
7	Ogbonnaya *et al*. (2024)	Filament extruder	Single screw (custom-built system)	1.75 mm	Filament was successfully spooled and printed	FlashForge Finder Lite	200 °C	Developed and optimized a low-cost extrusion setup for banana fibre-HDPE filaments	Printability issues with higher fibre content; limited mechanical evaluation
8	Ademoroti (2024)	Mini filament extruder with dual-zone heating	Single screw (machined mild steel, chain-driven, 3.2:1 gear ratio)	1.75 ± 0.05 mm	Not directly tested in 3D printer but filament was successfully extruded and spooled	Not applicable (extruder only developed)	220 °C (hopper zone), 200 °C (nozzle zone)	Designed a low-cost mini extruder using recycled HDPE; achieved consistent filament diameter and defined extrusion parameters	No printability or mechanical testing done; winding was manual; extrusion rate still relatively low (0.17 kg/hr)

https://doi.org/10.70118/ujet.2026.sp01.08

2.2.4 Operating Temperature and Process Conditions

The extrusion and printing temperatures reported in these studies fall within the expected range for HDPE: typically, 180–240 °C for the nozzle and 70–80 °C for the print bed. Maintaining thermal stability during extrusion is essential to prevent degradation of the polymer and ensure proper fibre dispersion. Sonjaya *et al*. (2021) successfully extruded and printed coconut fibre-reinforced HDPE at 220 °C, with a bed temperature of 70 °C, achieving minimal warping. These values reflect the delicate balance required when processing recycled HDPE, which can degrade if overheated but may exhibit poor flow if under-heated.

Additionally, Ademoroti (2024) and Esan (2024) used dual-zone heating to control temperatures separately at the hopper and nozzle zones, aiming for better melt homogeneity and extrusion consistency. Their setup achieved good filament diameter control but lacked spooling and printing validation, suggesting a need for integrated systems that allow continuous extrusion, winding, and print testing.

3 Agricultural Fibres as Natural Fillers

The use of agricultural fibres as fillers in recycled plastics has gained increasing attention in the development of environmentally friendly 3D printing materials. Although plastic recycling is an effective solution to reducing plastic waste, the process often leads to a loss in key mechanical properties such as tensile strength and impact resistance. To overcome these limitations, researchers have explored the integration of natural fibres, derived from agricultural by-products, into recycled polymers. These fibres provide not only structural reinforcement but also offer the advantages of biodegradability, cost-effectiveness, and sustainability.

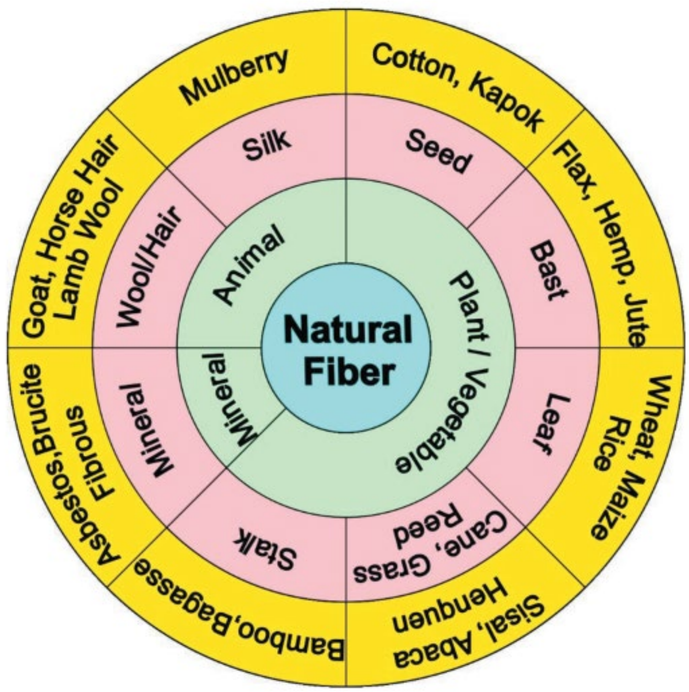

Figure 1: Classification of Natural Fibres (Chokshi *et al*. 2020)

A variety of agricultural fibres have been successfully used to reinforce thermoplastic composites (Figure 1). These include pineapple leaf fibre, coconut husk, melon husk, bagasse, rice husk, corn husk, flax fibre, banana fibre, hemp fibre, and wood-derived materials such as those from disposable chopsticks. These fibres are often sourced from post-harvest waste or agro-industrial by-products, making them an abundant and low-cost alternative to synthetic fillers. Their successful application in 3D printing filaments has been demonstrated across different polymer matrices, including recycled high-density polyethylene (HDPE).

Natural fibres typically consist of three main components: cellulose, hemicellulose, and lignin. Cellulose is the most abundant component and contributes to the mechanical strength and stiffness of the fibre due to its high crystallinity. Hemicellulose is a more amorphous polymer that plays a role in moisture absorption and affects the

https://doi.org/10.70118/ujet.2026.sp01.08

thermal stability of the fibre. Lignin, on the other hand, is a complex aromatic polymer that provides rigidity and water resistance but can inhibit bonding between the fibre and plastic matrix. The ratio of these three components varies depending on the source of the fibre and greatly influences its behaviour when incorporated into composite materials. To improve the compatibility of natural fibres with hydrophobic plastic matrices, various pre-treatment techniques are employed. Alkali treatment, commonly using sodium hydroxide (NaOH), is widely used to remove surface impurities such as lignin and hemicellulose, thus exposing more cellulose and increasing the fibre's surface roughness. This improves the adhesion between the fibre and the polymer during processing. For example, studies such as those by Beg *et al.,* (2024) and Tan *et al.,* (2023) found that alkali-treated hemp and wood fibres improved the overall mechanical properties and dimensional stability of PLA-based filaments.

Chemical treatments, including hydrogen peroxide and sodium silicate, have also been used to bleach or purify fibres, as reported by Leong *et al.,* (2021) and Rodriguez-Fabia *et al.,* (2022). These treatments may also influence the colour, degradation characteristics, and aesthetic appearance of the final filament. Additionally, thermal pre-treatment, particularly drying, is necessary to reduce the moisture content of the fibres. This is essential because high moisture levels can lead to swelling, debonding, and porosity during extrusion, as observed in Morales *et al.,* (2021) in their work with rice husk and recycled polypropylene.

3.1 Potential Benefits of Agro-Fibre-Reinforced Plastics

It should be emphasized that using fibres in recycled plastics offers multiple benefits related to mechanics and environmental safety. Firstly, these fibers provide enhanced tensile strength and increase modulus, prevent warping and reduce shrinkage during printing. Thus, according to the findings of Beg et al., (2024), hemp fibre reinforced PLA retained its performance during three recycling cycles without significant matrix-fibre separation. In addition, Yap et al., (2023) observed that a 2 wt% addition of corn husks provided the optimal performance with respect to the tensile strength of recycled poly-propylene rPP composites. At the same time, Morales et al., (2021) stated that the presence of rice husks reduced warping when 3D-printing using rPP-based filaments. Such characteristics are particularly useful when it comes to providing additional rigidity to printed parts during FFF. In addition to improved mechanical properties, it should be noted that the use of natural fibres reduces the amount of plastic waste in the environment, as they are fully biodegradable. Being easily renewable, these materials help to transition to a circular economy, in which agricultural waste and recycled plastic are repurposed to produce new composite filaments. From the economic perspective, natural fibers are relatively inexpensive because they are obtained from agricultural waste that does not need as much processing as synthetic counterparts. It will allow producing cheap filaments in larger amounts.

In addition to improved mechanical properties, fibre-reinforced plastics tend to have a stable thermal regime during manufacturing and 3D-printing processes, while dimensional accuracy increases as well. For instance, according to the research conducted by Navarrete et al., (2024) and Tanan et al., (2023), the treatment of fibres helped to enhance the thermomechanical properties of HDPE and polypropylene composite materials, reduce their shrinkage, and promote bonding. Nevertheless, it is crucial to manage fibre loading correctly, as too high concentrations might affect the quality of printing or reduce mechanical properties of the material. For instance, according to the studies by Leong et al., (2021) and Rodriguez-Fabia et al., (2022), high percentage of added fibres negatively impacted the quality of printed surfaces or made it brittle. Thus, fibre concentration is usually recommended to stay at 2% to 10%.

3.2 Mechanical and Thermal properties

The choice of reinforcement fibre plays a critical role in determining the performance of polymer composites, especially those derived from recycled thermoplastics such as HDPE. Natural fibres are gaining prominence due to their renewability, biodegradability, and relatively low environmental footprint. Table 2 summarises the physical (density and diameter), mechanical (tensile strength, Young's modulus, elongation at break), and thermal conductivity characteristics of commonly used natural and synthetic fibres, serving as a knowledge base for selecting suitable reinforcement materials in sustainable composite development.

Kenaf, hemp, flax, jute, sisal, and pineapple leaf fibre (PALF) are among the most researched natural fibres due to their favourable strength-to-weight ratios and bio-sourced origin. Kenaf fibres exhibit high tensile strength (up to 930 MPa) and a Young's modulus of 53 GPa, with relatively low elongation at break (~1.6%). Its moderate density (1.2–1.45 g/cm^3) and thermal conductivity (0.044 W/mK) make it suitable for structural applications

https://doi.org/10.70118/ujet.2026.sp01.08

where high stiffness and insulation are valued. Hemp fibres also display impressive mechanical performance, with tensile strengths ranging from 550 to 900 MPa and an exceptionally high Young's modulus of up to 70 GPa. The elongation at break (1.6–4.0%) suggests slightly better ductility than kenaf. With low thermal conductivity (~0.04 W/mK), hemp is suitable for composites requiring both mechanical strength and thermal resistance. Flax, a widely used bast fibre, demonstrates a broad range in tensile strength (345–1500 MPa), a modulus of 27.6 GPa, and elongation between 2.7–3.2%. These values suggest that flax is one of the more versatile fibres for reinforcing thermoplastics. Similar fibres like jute and sisal exhibit moderate to high tensile strengths (up to 800 MPa and 700 MPa, respectively) but typically show lower stiffness, making them better suited for semi-structural and packaging applications.

Cotton, while not traditionally used in structural composites, shows tensile strengths between 287 and 800 MPa and a low modulus (5.5–12.6 GPa), suggesting its potential in flexible or cushioning applications. The fibre's relatively high elongation (up to 10%) supports its suitability for impact-absorbing or soft composite applications. Pineapple leaf fibre (PALF) stands out with an extraordinarily high tensile strength range (170–1627 MPa) and modulus values between 60–82.5 GPa, indicating high stiffness and strength. Its relatively low density (1.25 g/cm^3) enhances its utility in lightweight composites. Other natural fibres like banana, ramie, abaca, bamboo, and bagasse offer intermediate to low tensile properties but are useful in specific applications. Banana fibres show tensile strengths between 7.7 and 32 MPa and moderate ductility, making them suitable for low-load bearing and biodegradable composites. Ramie and abaca fibres, on the other hand, offer higher strength (up to 128 MPa and 70 MPa, respectively) with better ductility, while bamboo offers a balance of strength and low density. Bagasse, derived from sugarcane waste, is one of the least dense and lowest strength fibres, limiting its use to non-structural applications.

Coconut fibre and coir—commonly used in consumer and automotive products—demonstrate relatively low strength and modulus but possess excellent energy absorption capacity due to high elongation. Coir, for instance, shows elongation between 15–51%, making it ideal for shock-absorbing or impact-prone environments. Thermal conductivity is crucial for evaluating a fibre's insulation capacity or heat dissipation potential. Natural fibres generally exhibit low thermal conductivity, typically ranging between 0.038 and 0.044 W/mK, which makes them good insulators. Flax, jute, hemp, and kenaf fall within this range, supporting their use in thermally resistant panels, boards, and housings. From the comparative table, it is evident that natural fibres offer an attractive balance between mechanical performance, thermal resistance, low density, and environmental benefits. While synthetic fibres like carbon and E-glass outperform in strength and modulus, their environmental impact and cost limit their use in sustainable composites. Fibres such as flax, hemp, PALF, and kenaf stand out for structural applications, whereas coir, banana, and bagasse are better suited for flexible, low-strength, or biodegradable composites. Selecting the appropriate fibre for reinforcing recycled HDPE or other matrices depends on the specific property trade-offs required in the final application, including mechanical load-bearing, thermal resistance, weight, and sustainability objectives.

https://doi.org/10.70118/ujet.2026.sp01.08

Table 2: Mechanical and Thermal Properties of Agricultural Fibres (Chokshi et al., 2020; Aida et al., 2021; Akil et al., 2011; Mahjoub et al., 2014; Sab et al., 2015; Siakeng et al., 2019; Ghosh et al., 2016)

Fibre	Density (g/cm³)	Diameter (μm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Thermal Conductivity (W/mK)
Kenaf	1.2–1.45	20–200	930	53	1.6	0.044
Hemp	1.47–1.48	25–500	550–900	70	1.6–4.0	0.04
Flax	1.4–1.5	40–600	345–1500	27.6	2.7–3.2	0.038–0.040
Cotton	1.5–1.6		287–800	5.5–12.6	3.0–10.0	
Jute	1.3–1.6		393–800	10–30	1.16–1.8	0.038–0.040
Sisal	1.45–1.5		400–700	9.0–38.0	2.0–14.0	
PALF	1.25		170–1627	60–82.5	1.6–2.4	
Carbon (standard)	1.4–1.78		4000–4800	230–427	1.4–1.8	
E-glass	2.50–2.55		2000–3500	70–73	2.5–3.2	
Pineapple	0.8-1.6		170-1627	1.44-82.0	0.8-14.5	
Ramie	1.00-1.55		220-1000	23-128	1.20-4.00	
Abaca	1.5		400-980	6.2-70.0	3.0-12.0	
Bagasse	0.55-1.25		20-350	0.5-27.10	0.9-5.8	
Bamboo	0.6-1.1		140-800	11.00-35.91	1.3-7.0	
Banana	0.75-1.35		54-914	7.7-32.0	1.00-9.00	
Coconut	0.38-1.10		83.0-222.0	12.0-32.0	-	0.043
Coir	1.2-1.5		95-593	2.8-6.00	15-51.40	

https://doi.org/10.70118/ujet.2026.sp01.08

3.3 Chemical Composition of Fibres

The chemical composition of natural fibres (NFs) plays a fundamental role in determining their suitability as reinforcements in polymer composites, particularly in recycled plastics like high-density polyethylene (HDPE). A comprehensive analysis of over 50 different fibres, as presented in the table, highlights significant variability in cellulose, lignin, hemicellulose, pectin, wax, moisture, ash content, and microfibrillar angle, all of which influence a fibre's mechanical performance, compatibility with polymer matrices, and processing behaviour. Cellulose content, a key contributor to tensile strength and stiffness, ranges from 26% to 91% across the surveyed fibres as shon in Table 3. Fibres like *Ramie* (68 – 91%), *Cotton* (82.7 – 90%), *Sansevieria* (79.7 – 80%), and *Flax* (64.1 – 71.9%) exhibit high cellulose levels, suggesting strong potential for reinforcement in HDPE composites. High cellulose not only improves strength but also enhances thermal stability and resistance to creep. On the other end, fibres such as *Bamboo* (26 – 43%) and *Coconut tree leaf sheath* (27%) are relatively low in cellulose, which may limit their contribution to mechanical performance unless chemically treated or used in hybrid composites.

Lignin content, responsible for rigidity and decay resistance, varies dramatically from as low as 0.6% in *Ramie* to over 45% in *Piassava* and *Kenaf*. High lignin levels, while advantageous for dimensional stability and water resistance, may complicate processing due to lower thermal degradation thresholds and increased brittleness. In bio-composites, a balance between cellulose and lignin is essential: fibres such as *Jute* (12 – 14% lignin) and *Flax* (2 – 22%) provide a good compromise, combining strength with workable processing characteristics.

Hemicellulose, often associated with moisture absorption, spans a wide range of 3 – 38.5%. Fibres with lower hemicellulose content, such as *Ramie* (0.5 – 16.7%) and *Agave* (4.85%), are better suited for outdoor or humid applications due to reduced susceptibility to water uptake. Excessive hemicellulose, as seen in *Alfa* (38.5%), could lead to higher moisture content, adversely affecting dimensional stability and interface bonding in composites. Additionally, moisture content across fibres varies widely, with *Coir* containing up to 11.36% and *Sansevieria* with only about 3.08%. This metric is critical in composite fabrication, as excessive moisture can lead to void formation during extrusion or moulding.

Another chemical indicator, pectin content, though reported sparsely, is significant in fibres like *Ramie* (1.9%), *Flax* (1.8–2.3%), and *Phormium tenax* (0.7%). Pectins may aid in forming hydrogen bonds at the fibre–matrix interface, thereby enhancing adhesion, although they can also contribute to moisture sensitivity. Wax content, typically ranging from 0.09–4.0%, affects fibre surface energy and interfacial bonding with hydrophobic polymers. Low wax fibres like *Sansevieria cylindrica* (0.09%) provide better compatibility, whereas higher wax content, as in *Oil palm* (4.0%), may require surface treatments to improve matrix adhesion.

Ash content, indicative of inorganic impurities or mineral residue, varies between 0.6% and 8%, with *Rice husk* showing the highest at 20%. High ash fibres may influence thermal conductivity and flame resistance, but can negatively impact mechanical properties and increase tool wear during processing. Lastly, the microfibrillar angle (MFA) — a critical structural property — is only reported for a few fibres like *Coir* (30.45°), *Banana* (11 – 12°), and *Rachilla* (35 – 39°). Fibres with lower MFA, such as *Banana*, tend to exhibit higher stiffness and tensile modulus due to better alignment of cellulose fibrils along the fibre axis.

The compositional diversity among natural fibres means there is no universally optimal fibre; the choice must align with the specific requirements of the polymer matrix and intended application. High-cellulose, low-lignin fibres like *Flax*, *Jute*, and *Hemp* offer a good balance for structural reinforcement, while high-ash or high-pectin fibres might be reserved for niche applications where thermal or biodegradability properties are prioritised. The chemical complexity presented in this data reinforces the need for pre-treatment or hybridisation strategies when incorporating natural fibres into recycled HDPE for 3D printing or injection moulding applications.

https://doi.org/10.70118/ujet.2026.sp01.08

Table 3: Chemical Composition of Natural Fibres (Chokshi et al., 2020; Loganathan et al., 2020; Pereira et al., 2015; Pickering 2008; Rowell and Stout 2007; Sathishkumar et al.,2013)

NF	Cellulose (%)	Lignin (%)	Hemi Cellulose (%)	Pectin (%)	Wax (%)	Moisture (%)	Ash (%)	Microfibrillar angle (°)
Sansevieria ehrenbergii	80.00	7.80	11.25	0.45	-	10.55	0.60	19.00
Kenaf	45.00–57.00	21.50	8.00–13.00	0.60	0.80	6.20–12.00	2.00–5.00	2.00–6.20
Jute	58.00–63.00	12.00–14.00	21.00–24.00	-	-	-	-	-
Hemp	70.20–74.40	3.70–5.70	17.90–22.40	0.90	0.80	6.20–12.00	0.80	2.00–6.20
Phormium tenax	45.10–72.00	11.20	30.10	0.70	0.70	10.00	-	-
Flax	64.10–71.90	2.00–2.20	18.60–20.60	1.80–2.30	1.70	8.00–12.00	-	5.00–10.00
Agave	68.42	4.85	4.85	-	0.26	7.69	-	-
Bamboo	26.00–43.00	1.00–31.00	30.00	-	-	9.16	-	-
Sea grass	57.00	5.00	38.00	10.00	-	-	-	-
Ramie	68.60–91.00	0.60–0.70	5.00–16.70	1.90	-	-	-	69.00–83.00
Abaca	56.00–63.00	7.00–9.00	20.00–25.00	-	3.00	-	-	-
Alfa	45.40	14.90	38.50	-	2.00	-	-	-
Wheat Straw	51.00	16.00	26.00	-	-	-	-	-
Sisal	78.00	8.00	10.00	-	2.00	11.00	1.00	20.00–25.00
Sansevieria cylindrica	79.70	3.80	10.13	-	0.09	3.08	-	-
Oil palm	65.00	17.50	10.12	-	4.00	-	-	-
Henequen	60.00	8.00	28.00	-	0.50	-	-	-
Curaua	73.60	7.50	9.90	-	-	-	-	-
Coconut tree leaf sheath	27.00	27.70	14.00	-	-	4.70	-	-
Piassava	28.60	45.00	25.80	-	-	-	-	-
Kudzu	33.00	14.00	11.60	-	-	-	-	-
Cotton	82.70–90.00	-	3.00	-	0.60	7.85–8.50	-	-
Nettle	86.00	-	10.00	-	4.00	-	-	-
Rice husk	38.00–45.00	-	12.20	-	-	-	20.00	-
Oil Palm	65.00	29.00	-	-	-	-	-	-
Isora	74.00	23.00	-	-	1.09	-	-	-
Oat	31.00–48.00	16.00–19.00	-	-	-	-	6.00–8.00	-
Coniferous	40.00–45.00	26.00–34.00	-	-	-	-	-	-
Coir	37.00	42.00	-	-	-	11.36	-	30.45
Banana	83.00	5.00	-	-	-	10.71	-	11.00–12.00
Petiole bark	46.00	12.00	-	-	-	-	-	20.00–21.00
Rachis	42.75	26.00	-	-	-	-	-	28.00–37.00
Rachilla	42.00	16.00	-	-	-	-	-	35.00–39.00
Coniferous	40.00–45.00	26.00–34.00	-	-	-	-	-	-
Deciduous	38.00–49.00	23.00–30.00	-	-	-	-	-	-
Sugar	32.00–48.00	19.00–24.00	-	-	-	-	1.50–5.0	-
Barley	31.00–45.00	14.00–15.00	-	-	-	-	5.00–7.00	-
Rye	33.00–50.00	16.00–19.00	-	-	-	-	6.00–8.00	-
Esparto	33.00–38.00	17.00–19.00	-	-	-	-	6.00–8.00	-
Sabai	-	22.00	-	-	-	-	6.00	-
Phragmites communis	44.00–46.00	22.00–24.00	-	-	-	-	3.00	-
Coniferous	40.00–45.00	26.00–34.00	-	-	-	-	<1.00	-
Deciduous	38.00–49.00	23.00–30.00	-	-	-	-	<1.00	-
Cytostachys renda (leaf stalk)	38.99	18.24	19.15	-	-	-	-	-
Phychosperma macarthurii (leaf stalk)	36.42	14.22	20.79	-	-	-	-	-
Range:	**26.00–91.00**	**0.60–45.00**	**3.00–38.50**	**0.45–10.00**	**0.09–4.00**	**3.08–12.00**	**0.60–8.00**	**2.00–83.00**

https://doi.org/10.70118/ujet.2026.sp01.08

4 HDPE Composites with Natural Fibre Additives

4.1 Research on recycled high-density polyethylene (HDPE) and its composites

Research on recycled high-density polyethylene (HDPE) and its composites continues to expand as researchers explore sustainable alternatives for polymer reinforcement and 3D printing applications. Several studies as shown in Table 4 have examined both synthetic and natural reinforcements with recycled HDPE, focusing on mechanical, thermal, structural, and morphological performance, as well as processability in filament production and additive manufacturing. Anokwu (2019) investigated the incorporation of bentonite nanoclay into HDPE and found a significant improvement in tensile strength and modulus, particularly at a 10% filler concentration. However, elongation decreased, indicating reduced ductility, and the study did not explore filler levels beyond 20%. This synthetic nanoclay composite was tested as a specimen, rather than filament, and presents a viable route for stiffness-driven applications. Chong et al. (2016) focused on recycled HDPE for filament development, conducting thermal and spectroscopic tests including Differential Scanning Calorimetry (DSC), thermogravimetric analysis (TGA), Fourier Transform Infrared Spectroscopy (FTIR) , and Raman spectroscopy. While the thermal properties were stable and the material showed low water absorption, issues such as warping and bed adhesion during 3D printing persisted. Despite these limitations, the study demonstrated the feasibility of recycled HDPE filaments for additive manufacturing. In a study by Cynthia et al. (2017), prodegradant additives (d2w®) were used with HDPE to enhance environmental degradability. The additives delayed oxidation and degradation, particularly at ambient temperature (25 °C), but the material failed to degrade significantly in landfill or composting conditions. These results show that while additive-based composites improve lifetime control, they are highly dependent on oxygen-rich environments.

Suvari and Gurvardar (2024) introduced natural cotton yarn into HDPE to form hybrid yarn composites. Their tensile tests showed strength comparable to virgin HDPE and a 36% improvement over cotton yarn alone. However, standalone recycled HDPE filaments still lagged behind virgin polymer performance. This underscores the importance of reinforcement, especially natural fibres, in enhancing recycled polymer capabilities for filament applications. The research by Yi et al. (2022) examined coconut fibre-reinforced HDPE composites for floor tile production. The specimens showed promising mechanical, thermal, and moisture-resistant properties, making them suitable for outdoor use. However, the study did not extensively explore fibre content optimisation or long-term performance, leaving room for further development in real-world durability. Arantes et al. (2018) studied the incorporation of babassu coconut epicarp fibre into HDPE/EVA foam blends. Mechanical and morphological testing revealed structural improvements, although application-specific tests or aging performance were not addressed. This highlights the potential of hybrid natural-synthetic matrices but points to a need for broader validation. In the work of Dalloul et al. (2022), cellulose nanofibrils (CNF) modified with PSA were introduced into HDPE for filament production. The result was a 23% increase in modulus and reduced warping. Despite this promising performance, the formulation required complex synthesis steps, and printability depended on tight formulation control, limiting practical scalability.

Xanthopoulou et al. (2023) developed hemp fibre-reinforced HDPE composites and found a threefold increase in modulus, alongside antioxidant activity. However, the absence of compatibilizers caused fibre–matrix adhesion issues. This study emphasises the dual role of fibre in enhancing mechanical and chemical properties, while also revealing compatibility challenges. Arendra et al. (2019) explored the effect of heating temperature and screw speed on filament roundness and diameter uniformity during extrusion of recycled HDPE. Although only geometric properties were analysed, the work established key process parameters for filament quality, indicating that process conditions are crucial even in the absence of reinforcement. Setiawan et al. (2021) implemented a PID-based temperature control system for HDPE extrusion using CNC-based machines. While the study successfully achieved continuous extrusion at 200 °C through a 2 mm nozzle, it did not evaluate the mechanical quality of the resulting filaments or printed parts. This study offers valuable insights into hardware design and process control in filament production.

https://doi.org/10.70118/ujet.2026.sp01.08

Table 4: Overview of Recycled HDPE Composite Filament and Specimen Research

S/N	Author	Tests carried out	Findings	Limitations	Composites used	Type of reinforcement	Final product (specimen or filament)
1	Anokwu (2019)	Tensile testing, SEM analysis	Nanoclay improved tensile strength and modulus of HDPE, best results at 10% filler	Reduction in elongation; tested only up to 20% filler	HDPE + Bentonite nanoclay	Synthetic (nanoclay)	Specimen
2	Chong et al. (2016)	DSC, TGA, FTIR, Raman spectroscopy, water absorption, extrusion tests	Recycled HDPE filament is viable with stable thermal properties and low water absorption	Warping and adhesion issues in 3D printing still present	Recycled HDPE	None	Filament
3	Cynthia et al. (2017)	DSC, FTIR, SEM, Rheometry, Oxidation Onset Temperature	d2wÂ® additive delayed degradation; better lifetime at 25 °C	No biodegradation in landfill or composting; limited to oxygen exposure	HDPE + prodegradant	Synthetic (additive)	Specimen
4	Suvari and Gurvardar (2024)	Tensile tests, hybrid yarn formation, statistical analysis	Hybrid yarns with cotton matched virgin HDPE strength; 36% stronger than cotton yarn alone	Recycled filament alone had lower strength than virgin	HDPE + cotton yarn	Natural (cotton yarn)	Filament
5	Yi et al. (2022)	Tensile, flexural, impact, hardness, water absorption, thermal insulation tests	Coconut fiber reinforced HDPE suitable for outdoor floor tiles	Optimal fiber ratio not deeply explored; no long-term durability test	HDPE + coconut fiber	Natural (coconut fiber)	Specimen (floor tiles)
6	Arantes et al. (2018)	Mechanical testing, morphology, thermal analysis	Babassu fiber improved structure and mechanical properties of HDPE/EVA foam	Specific application and durability not assessed	HDPE/EVA + babassu coconut epicarp fiber	Natural (babassu fiber)	Specimen

https://doi.org/10.70118/ujet.2026.sp01.08

7	Dalloul et al. (2022)	Mechanical testing, SEM, contact angle, FTIR, NMR, warping analysis	CNF improved modulus by 23% and reduced warping in HDPE filament	Complex synthesis steps; printability dependent on precise formulation	HDPE + CNF-PSA (modified cellulose nanofibrils)	Natural (cellulose nanofibrils)	Filament
8	Xanthopoulou et al. (2023)	Mechanical, thermal, antioxidant, degradation tests; SEM	Hemp fiber composites had up to 3x modulus and high antioxidant activity	Adhesion issues without compatibilizer; variable fiber quality	HDPE + hemp fibers	Natural (hemp)	Specimen
9	Arendra et al. (2019)	Effect of heating temperature and screw speed on filament roundness and diameter uniformity	Heating temperature and screw speed both significantly influenced filament roundness; only heating temperature affected diameter uniformity	Focus was only on geometric properties, not mechanical or thermal properties	Recycled HDPE	None	Filament
10	Setiawan et al. (2021)	PID-based temperature control for HDPE extrusion with plastic pellets	System successfully melted HDPE at 200 °C and extruded through 2mm nozzle using CNC-driven extruder	No mechanical testing of filaments or printed parts conducted	HDPE pellets	None	Filament
11	Gunesegeran et al. (2022)	Production of HDPE tiles from recycled materials	Demonstrated a sustainable reuse method for HDPE in tile production	No mention of filament or 3D print application	Recycled HDPE	None	Specimen (Tiles)
12	Kumar et al. (2022)	Thermal and mechanical testing (tensile, flexural, TGA, MFI) on MWCNT/HDPE nanocomposites	MWCNT addition increased thermal stability and mechanical strength (tensile, flexural)	Used functionalized MWCNTs; potential cost and dispersion challenges not addressed	HDPE + MWCNT (0.5 - 5 wt.%)	Synthetic (MWCNT)	Both filament and specimen

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13	Rubiano-Navarrete et al. (2024)	Tensile testing, FTIR, SEM, TGA, DSC	Adding banana fiber to HDPEr reduced tensile strength but increased strain; thermal stability decreased with fiber	Low interfacial bonding led to reduced mechanical strength; lower modulus with fiber	Recycled HDPE + 10-20% banana fiber	Natural (banana fiber)	Specimen
14	Ahmed and Ali (2024)	Tensile and flexural testing (ASTM D638-22, D790-17)	Recycled HDPE showed 14.25 MPa tensile strength and 32.63 MPa flexural strength; suitable for building products	Void formation due to extrusion delays; no reinforcement used	Recycled HDPE	None	Specimen
15	Somide (2025)	FTIR, SEM and XRD	Adding Melon husk fiber to HDPEr showed optimum performance at 6% loading	No thermal and mechanical testing of filaments wasconducted	Recycled HDPE + 2-10% Melon husk fiber	Natural (Melon husk fiber)	Filament

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Gunesegeran et al. (2022) focused on repurposing recycled HDPE into tiles and demonstrated a practical reuse application. While the study successfully produced tiles from recycled plastic, it did not extend to filament development or 3D printing relevance, limiting its contribution to additive manufacturing research. In Kumar et al. (2022), multi-walled carbon nanotubes (MWCNTs) were incorporated into HDPE to evaluate improvements in mechanical and thermal behaviour. Tensile and flexural strengths, as well as thermal stability, improved with increasing MWCNT content. However, the cost of functionalised MWCNTs and potential dispersion challenges were noted. This study showed potential for high-performance HDPE-based filaments and specimens when cost and processability are addressed. Rubiano-Navarrete et al. (2024) incorporated banana fibre into recycled HDPE and reported reduced tensile strength but increased strain-to-failure. The thermal stability declined, and weak interfacial bonding contributed to a lower modulus. These findings suggest that while natural fibre reinforcement can improve ductility, it requires adequate compatibilisation to maintain strength. Ahmed and Ali (2024) investigated the mechanical properties of recycled HDPE specimens without any reinforcement and reported tensile and flexural strengths of 14.25 MPa and 32.63 MPa, respectively. However, extrusion delays led to void formation, and no reinforcement was included. This study provides a baseline for recycled HDPE's performance but highlights the need for improved process control and structural enhancement.

Recent undergraduate projects, such as those by Somide (2025) and Muiz (2025), explored the incorporation of Melon husk and Rice husk fibres into recycled HDPE filaments. Both studies utilised FTIR, SEM, and XRD to characterise fibre dispersion, chemical bonding, and crystallinity. The findings showed increased polar group presence, microstructural changes, and crystallinity reduction with higher fibre loading. These works highlight the challenges and opportunities in natural fibre reinforcement, especially concerning interfacial bonding and dispersion quality

The hydrophilic nature of natural fibres creates interfacial adhesion challenges when blended with hydrophobic polymers like HDPE. To address this, compatibilisers such as maleic anhydride-grafted polyethylene (MAPE) are often incorporated to improve fibre-matrix bonding. (Xanthopoulou *et al.,* (2023) demonstrated that using polyethylene-grafted maleic anhydride (PE-g-MA) with hemp fibres significantly improved the interfacial adhesion and print performance of HDPE filaments. Other additives may include plasticisers to enhance flowability, UV stabilisers for outdoor applications, or colourants depending on the intended use of the filament. These additives must be optimised to avoid compromising filament strength or print quality. Similarly, Dalloul *et al.,* (2022) used polymer-modified cellulose nanofibrils as an additive to improve the 3D printability of HDPE composites, leading to better tensile performance and reduced warping. Ahmad et al. (2023) highlight that additive inclusion such as nanocellulose, coupling agents, or plasticisers not only enhances mechanical properties but also improves dimensional stability during filament extrusion and 3D printing.

5 Conclusion and Recommendations

The reviewed literature demonstrates that incorporating agricultural fibres into recycled HDPE presents a viable and sustainable approach for composite filament development in additive manufacturing. Studies consistently showed that natural fibres such as melon husk, banana, hemp, coconut, and rice husk can mitigate key challenges associated with recycled HDPE, including warping, shrinkage, and poor interlayer bonding, particularly at moderate fibre loading levels of 2–10 wt%. Characterisation studies employing SEM, FTIR, and XRD confirmed improvements in microstructural integrity, chemical compatibility, and crystallinity when fibres were properly pre-treated using alkali or other surface modification techniques. The evidence from reviewed works, including those by Xanthopoulou et al. (2023), Dalloul et al. (2022), Rubiano-Navarrete et al. (2024), Somide (2025), and Ogbonnaya et al. (2024), establishes that agro-fibre-reinforced HDPE filaments offer both mechanical and environmental benefits, supporting a circular economy model that repurposes agricultural waste and recycled plastic into functional 3D printing materials. Future work should prioritise fibre loading optimisation, compatibiliser selection, and scaled-up filament production to advance the commercial viability of these sustainable composites.

Based on the evidence from reviewed studies, future research should focus on optimising fibre loading levels, surface treatment techniques, and compatibiliser usage to maximise mechanical performance without compromising printability. The reviewed works highlight a recurring gap in standardised mechanical and thermal testing protocols for agro-fibre-reinforced filaments; addressing this will strengthen cross-study comparability. Investigations into hybrid composites combining two or more fibres may reveal synergistic effects

https://doi.org/10.70118/ujet.2026.sp01.08

that enhance structural and thermal behaviour, as indicated by emerging studies on melon husk and rice husk reinforcements. Furthermore, long-term durability assessments, biodegradation studies, and life cycle analyses should be prioritised to validate real-world applicability and environmental benefit claims. Research should also explore automation and upscaling of filament production from recycled and agro-based materials to support commercial-scale sustainable manufacturing.

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