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Enhancing The Mechanical Properties Of Pla: A Study On Custard Apple Seed Filler As A Sustainable Additive For 3d Printing Filaments

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Abstract: This paper focuses on investigating a new bio-based filler founded on custard apple seed powder which can be used to improve the mechanical strength of PLA filaments for the process of FDM 3D printing. The results show that seeds of the fruit hold 15.43% crude fiber and many chemical compounds useful for its bioactivity. Fine powder obtained through grinding the seeds is, therefore, compounded with the matrix of PLA in various concentrations. The optimization process of the filler preparation was based on the physical properties of the seeds, including the average particle size at 7.76 mm and sphericity at 0.59. Chemical analysis indicated the presence of phenolic compounds with a concentration of 42.02 mg GAE/100g and other bioactive components, possibly having antioxidant properties, which would enhance the stability of the polymer. The tensile strength, flexural properties, and impact resistance of the PLA composites were found to be significantly improved by the addition of custard apple seed filler. The optimized composite formulation offered superior mechanical performance while retaining the biodegradability of the material. The thermal analysis showed enhanced thermal stability in the composites, which is attributed to the complex chemical composition of the seeds. It reports on an environmentally friendly approach for the conversion of agricultural waste to the reinforcement of characteristics of a 3D printed biodegradable material.

Keywords: Polylactic acid (PLA); Annona squamosa; Bio-based fillers; 3D printing filaments; Natural fiber composites; Mechanical properties; Sustainable additives; Biodegradable polymers; Fused deposition modeling (FDM).

I. INTRODUCTION

The rapid growth and technological maturity of additive manufacturing, specifically Fused Deposition Modeling (FDM) 3D printing, have created record demand for next-generation materials with superior mechanical properties. In this fast-changing environment, Polylactic Acid (PLA) has emerged as a leading biomaterial, attracting much attention because of its complete biodegradability and origin from renewable farm resources[1]. This makes PLA an eco-friendly substitute for petroleum-derived polymers for various applications across various industries. However, for all its environmental benefits, PLA is plagued by inherent structural drawbacks most notably inorganic brittleness, inadequate impact resistance, and thermal stability compromised that severely limit its application in demanding industrial environments and long-term functional devices where performance cannot

be compromised[2].

1.1 THE PERFORMANCE GAP IN CURRENT PLA APPLICATIONS

The inherent mechanical shortcomings intrinsic to unreinforced PLA appear most problematic in high-performance engineering applications requiring superior mechanical toughness, impact absorption, and thermal endurance. Traditional PLA formulations usually exhibit tensile strength values of 50-60 MPa, with critically constrained elongation at break percentages not often in excess of 10%, and modest impact strength measurements of about 2.5-3 kJ/m²[3]. In addition, its relatively low glass transition temperature usually in the range of 55-60°C places very stringent constraints on its functional feasibility in high-temperature environments or thermal cycling applications[4]. Although these properties are sufficient for prototyping demonstrations and non-critical applications requiring little stress, they are significantly below the performance levels required for advanced engineering implementations where structural integrity under varied loading conditions takes precedence[5].

1.2 ENVIRONMENTALLY RESPONSIBLE PROPERTY IMPROVEMENT STRATEGIES

Traditional methods used to strengthen polymer mechanical properties often include addition of synthetic additives such as glass fibers, carbon nanostructures, mineral particulates, or metallic fillers[6]. These traditional reinforcement methods inherently undermine the biodegradability profile and environmental benefits that represent PLA's key competitive edge in the sustainability-oriented materials market[7].

This inherent contradiction has spurred extensive research efforts aimed at investigating naturally-sourced, bio-based fillers as effective substitutes for property improvement without compromising environmental compatibility[8]. Agricultural co-products and processing residues are outstanding candidate materials for this niche use because they are broadly available, cost-effective, and ideally suited to circular economy principles that are increasingly informing industrial choice[9].

Repurposing these agricultural waste streams strategically provides twin environmental advantages of improving the performance properties of biodegradable polymers while solving agricultural waste management problems through value-added material transformation[10]. This strategy is a prime example of the incorporation of sustainability factors throughout the whole material life cycle, from the first biomass acquisition to processing and final biodegradation[11].

1.3 MULTIFACETED TECHNICAL BARRIERS IN BIOCOMPOSITE FILAMENT DEVELOPMENT

Achievement of high-performance bio-composite filaments designed precisely for FDM 3D printing technology requires researchers to confront a sophisticated set of technical hurdles different from those in traditional polymer processing[12]. In contrast, conventional manufacturing practices like injection molding or compression molding do not present such restrictive demands for material rheological performance to achieve uniform extrusion processes and stable Natural fillers should exhibit adequate thermal stability to be able to resist the high processing temperatures commonly between 180-220°C for PLA extrusion without degrading and losing their reinforcement effectiveness or generating unwanted byproducts that will impact print quality[13]. The compatibility of the hydrophilic natural fillers with the comparatively hydrophobic PLA matrix is another essential parameter controlling stress transfer efficiency and thereby affecting the final mechanical performance of the composite material[14].

In addition, printing parameters such as extrusion speed, layer thickness, infill structure, and density patterns need thorough recalibration specially designed for bio-composite materials, which differ considerably from those optimized for virgin polymers[15]. The intrinsic hygroscopicity typical of most natural fillers adds more complications, which may influence both initial filament manufacturing processes and subsequent printing performance through moisture-driven degradation mechanisms[16].

1.4 CUSTARD APPLE SEEDS: A REVOLUTIONARY BIOFILLER PLATFORM

This first-ever study introduces custard apple (*Annona squamosa* L.) seeds as a novel and not before used bio-based filler to improve PLA performance properties. Rigorous investigation shows several unique properties that place these crop waste products as exceptionally qualified for this niche application, far surpassing those of other traditional natural fillers previously explored[17].

1.5 MORPHOLOGICAL CONSISTENCY AND STRUCTURAL ARCHITECTURE

The striking morphological homogeneity of custard apple seeds, as manifested in their repeatedly reproducible sizes with averages of 13.17 mm length, 6.97 mm width, and 5.12 mm thickness, makes it possible for unusually uniform processing procedures and particle size control in grinding into a powdered state[18]. Their inherent architectural organization, expressed through an arithmetic mean diameter of 8.42 mm and sphericity ratio of 0.59, plays a crucial role in enhancing dispersion mechanics within the polymer matrix. This built-in structural order fosters more efficient stress transmission pathways through the composite material, possibly resulting in large improvements in mechanical load-carrying capability and deformation resistance against applied loads.

1.6 PHYTOCHEMICAL PROFILE AND REINFORCEMENT MECHANISMS

Elaborate biochemical profiling of custard apple seeds demonstrates a complex phytochemical composition with many components with potential to synergistically improve PLA performance properties by several reinforcement mechanisms[19]. The large natural fiber portion (15.43%) consisting mainly of cellulosic structures can serve as efficient mechanical reinforcing agents, potentially enhancing both tensile strength characteristics and elastic modulus values of the resulting composite. The high content of phenolic compounds (42.02 mg GAE/100g) with expressed antioxidant activity provides potential thermo-oxidative degradation mechanism protection during both processing under high temperature and the following application conditions, potentially prolonging component operating life[20].

The high protein content (20.01%) can theoretically change interfacial interaction kinetics between filler particles and the enveloping PLA matrix, enhancing adhesion properties and optimizing stress transfer efficiency across phase boundaries. Indigenous natural oils and other wax-like compounds naturally found in the seed structure can likely act as internal plasticizing agents, correcting the undesirable brittleness that normally accompanies PLA without requiring extra synthetic chemical additives that could compromise biodegradability or add deleterious ecological effects[21].

1.7 EXHAUSTIVE RESEARCH FRAMEWORK AND METHODOLOGICAL APPROACH

This interdisciplinary study seeks to methodically investigate and maximize the incorporation of custard apple seed powder into PLA matrices for FDM 3D printing purposes using a rigorously organized research approach involving several interlinked phases[22].

1.8 SOPHISTICATED MATERIAL FORMULATION AND CHARACTERIZATION PROTOCOLS

The study will utilize advanced seed powder preparation techniques, including precision-controlled drying regimens, optimized grinding parameters, and multi-stage sieving processes to obtain exactly tailored particle size distributions for composite filament extrusion without sacrificing reinforcement efficiency[23]. Extensive study of composite formulations will investigate filler concentration gradients from 1% to 20% by weight to determine optimal loading thresholds that balance improved mechanical properties with processing compatibility. Extensive characterization of materials will utilize several complementary analytical methods such as Fourier Transform Infrared (FTIR) spectroscopy for chemical interaction studies, Differential Scanning Calorimetry (DSC) for thermal transition behavior, Scanning Electron Microscopy (SEM) for interfacial morphology examination, and sophisticated rheological measurements to determine flow behavior under model processing conditions[24].

1.9 COMPREHENSIVE PROCESSING PARAMETER OPTIMIZATION FRAMEWORK

The study will determine absolute correlations between extrusion processing conditions and resulting filament quality characteristics through controlled variation of temperature profiles along multi-zone extrusion machines, screw rotation speed modifications, and precision-controlled cooling schemes. Optimization of printing parameters will explore intricate relationships between nozzle temperature controls, print head traversing speeds, layer thickness definitions, and judicious cooling interventions to achieve maximum dimensional precision and mechanical strength of produced components[25]. Further research of post-processing methods such as thermal annealing processes and surface treatments will investigate further potential for increasing mechanical properties via crystallinity optimization and interfacial strengthening processes[26].

1.10 MULTIFACETED PERFORMANCE EVALUATION METHODOLOGY

The studies will conduct systematic mechanical testing protocols strictly in conformity with international practices, such as tensile property characterization (ASTM D638), flexural behavior testing (ASTM D790), quantification of impact resistance (ASTM D256), and systematic hardness profile measurement at various scales[27].

Thermal stability testing will involve thermogravimetric analysis (TGA) to quantify decomposition kinetics and heat deflection temperature (HDT) testing to establish usable upper temperature thresholds for functional usage. Environmental durability testing will expose specimens to accelerated aging methodologies that include elevated humidity exposure, ultraviolet radiation cycling, and temperature cycling to forecast long-term performance characteristics under representative service conditions. Biodegradability verification via standardized test protocols will ensure retention of this critical ecological attribute in spite of material alteration[28].

1.11 EXPECTED RESEARCH CONTRIBUTIONS AND BROADER IMPLICATIONS

This innovative research has the potential to make several important contributions to green materials science and additive manufacturing technology. The creation of a completely new, eco-friendly composite material for FDM 3D printing purposes balancing significantly improved mechanical properties with retained biodegradability is a revolutionary leap in sustainable manufacturing technology[29]. The creation of detailed processing guidelines specifically targeting natural filler incorporation mechanics in PLA-based filaments will offer extremely valuable technical knowledge for future bio-composite development projects across the additive manufacturing industry[30].

This groundbreaking research will significantly contribute to the fast-growing discipline of sustainable material development for additive manufacturing purposes, with the potential to set methodological frameworks for a wide range of agricultural waste streams in need of similar technological upcycling[31]. The fundamental scientific understanding generated regarding the complex interrelationships between natural filler structural characteristics, processing parameter effects, and resultant mechanical property profiles in biodegradable polymer composites will significantly advance materials science knowledge in this critical research domain[32].

By methodically countering the core shortcomings of virgin PLA without jeopardizing its core environmental benefits, this study attempts to significantly enlarge the scope for real-world usability of biodegradable 3D printing technology to more advanced industrial applications globally, thus faster paving the way towards genuinely environmentally friendly manufacturing trends at the world level. The innovative use of agricultural waste streams as performance-enhancing additives also increases the sustainability value by addressing the problem of waste management at the same time that new value streams are created for agricultural producers.

II. LITERATURE SURVEY

Prashantha, et al. (2017) studied on the effectiveness of adding graphene to polylactic acid for the development of PLA/graphene nanocomposites, with significant enhancement in both thermal and mechanical properties. It was also indicated that adding 10% by weight graphene significantly enhanced the modulus and strength of the printed objects, proving its supremacy in terms of the printed material compared to neat PLA. These improvements are obviously attributed to the unique thermal and mechanical properties of graphene, further contributing to reinforcement of the PLA matrix as a whole. Results obtained herein further emphasize the possibility of incorporation of advanced fillers like graphene into PLA composite for superior material properties in 3D printing applications. This may be taken into account as part of a new basis to use natural and advanced fillers in improving the functionality of PLA, thus strengthening the growing interest in high-performance and versatile materials development in a new era of innovative additive manufacturing techniques.

Xu, et al. (2018) aimed at producing antioxidant bio-composite filaments based on PLA/lignin by the ink injection technique, with healthcare application in considerations like skin wound treatment. Lignin is a cross-linked aromatic polymer present in plant cell walls and has an intrinsic antioxidant property that could enhance the functionality of PLA-based materials. Lignin is added to PLA for the production of filaments with value-added properties, such as higher load-carrying capacity and better wettability, which are very important in healthcare applications requiring high mechanical strength and the material's ability to interface well with biological tissues. Consequently, the Bio-composite filaments were extensively tested in their mechanical performance, antioxidant

activity, and interaction with moisture. In fact, the load-bearing capacity was increased in the PLA filaments by incorporating lignin, which further increases their wettability. These features greatly enhance the possibilities of lignin-PLA composites for wound healing applications, where materials must support tissue repair and interact positively with body fluids. The current study emphasizes the potential of lignin, as a natural polymer, in developing advanced, functional materials for specific needs in medical and health areas.

Aqzina.S, et al. (2018) studied on the preparation of composites designed to improve the mechanical, electrical, and thermal properties of the generally badly performing 3D-printed objects regarding structural integrity. The specimen is formed by depositing layer after layer of molten ABS filament that contains fillers in it. The objective of the present study is to evaluate the influence of varying filler content on the mechanical, electrical, and thermal characteristics of ABS-zinc ferrite composites. The mechanical strength of such products in 3D printing is mostly weak, and the bonding between interlayers is also very fragile and brittle when compared to injection-molded products. The objective of this filler is therefore to reduce such deficiencies and hopefully enhance overall interface for 3D-printed composites, providing useful clues for future optimization of material properties with a target toward tougher and functional printed objects.

Gregor-Svetec D, et al. (2019) researched on the utilization of cardboard dust as a bio-filler for enhancing the properties of filaments produced from polylactic acid and high-density polyethylene for 3D printing. PLA and HDPE can be introduced into additive manufacturing broadly because they are versatile; however, they gain from improvements in mechanical strength and sustainability. The main goal of this study is to increase mechanical performance, such as tensile strength and rigidity, without losing printability by natural filler addition- cardboard dust. In this paper, the research carried out has been focused on showing that eco-friendliness of filaments, by adding cardboard dust, is increased. This gives feasibility for the sustainable choice mainly through waste material utilization. Also, the cardboard dust increases the overall stability and strength of the printed parts, thus minor. This approaches not only a reduction in waste but more importantly, a greener solution in enhancing the performance of the commonly used 3D printing materials such as PLA and HDPE.

Mazzanti V, et al. (2019) carried out the possibilities for enhancement of the mechanical properties of PLA with the use of natural fillers for 3D printing applications. Currently, PLA has become one of the most interesting biodegradable polymers due to environmental reasons. However, its mechanical properties can restrict its potential in an application. In this regard, natural fillers are sustainable and, therefore, similar to wood fillers, bamboo fibers, and agricultural waste, which can be relatively cheaply added to PLA for the enhancement of strength, stiffness, and impact resistance. The present review interprets these influencing factors: filler-matrix interaction, including size, distribution, and surface treatment of the filler, and their effect on printability and biodegradability properties of PLA filaments in detail. The results presented here underscored the potential of this natural filler-reinforced PLA for applications over a wider distance of 3D printed products, hence leading towards sustainability and a circular economy.

Gregor.D Svetec, et al. (2019) studied on mechanical improvements made to PLA filament using cardboard dust as a bio-filler. Cardboard dust which is obtained in recycling processes is high cellulose content thus providing an eco-sustainable alternative for enhancing PLA properties, one of the most used biodegradable polymers. Various amounts of cardboard dust were incorporated into the PLA matrix to produce composite filaments and consider their mechanical performance in this study. The tensile strength, impact resistance and bending strength tests have been used to determine how including cardboard dust affects structural integrity and durability of PLA filaments. Results show that compared to pure PLA, cardboard dust significantly improves its mechanical properties such as tensile strength and impact resistance. According to some studies conducted to examine the inclusion of such bio-composite materials like cellulose fibers found in them which help minimize brittleness while ensuring optimal load distribution within them, this improvement can be explained with reference to this fact. In addition, using recycled paper waste enhances its performance as well as sustainability whenever possible through recycling measures.

Domínguez-Robles, et al. (2019) investigated on this work aimed at producing antioxidant bio-composite filaments based on PLA/lignin by the ink injection technique, with healthcare application in considerations like skin wound treatment. Lignin is a cross-linked aromatic polymer present in plant cell walls and has an intrinsic antioxidant property that could enhance the functionality of PLA-based materials. Lignin is added to PLA for the production of filaments with value-added properties, such as higher load-carrying capacity and better wettability, which are very important in healthcare applications requiring high mechanical strength and the material's ability to interface well with biological tissues. Consequently, the Bio-composite filaments were extensively tested in their mechanical performance, antioxidant activity, and interaction with moisture. In fact, the load-bearing capacity was increased in the PLA filaments by incorporating lignin, which further increases their wettability. These features greatly enhance the possibilities of lignin-PLA composites for wound healing applications, where materials must support tissue repair and interact positively with body fluids. The current study emphasizes the potential of lignin, as a natural polymer, in developing advanced, functional materials for specific needs in medical and health areas.

Mimini, et al. (2019) explained the performance comparisons were made among the Kraft, Organize, and Lignosulfonate lignin incorporated into PLA composites based on the effect of these lignin on the properties of the materials. It was demonstrated through this work that, among the three types of lignin tested, the Organize lignin had the best compatibility with PLA. It also showed improved thermal stability compared to the other two lignin. It is because of this favorable interaction between the Organize lignin and PLA that stability with respect to high temperatures is improved. While these improvements in thermal properties and compatibility are indeed made, none of the lignin types could cause significant improvement in the flexural strength of PLA composites. The lack of contribution to increased flexural strength could be attributed to the fact that while lignin could modify some attributes of the PLA composites. These findings will provide yet more insight into the trade-offs entailed by the use of different types of lignin as fillers in PLA and point out the need for further research to optimize lignin-based composites for applications where improved mechanical properties would be required.

Miroslav Müller, et al. (2020) considered as an advanced technology, in the case of AM, research is conducted in two main directions: that of modification of the printing materials and the evaluation of the mechanical property, expressively in relation to the production parameters and technologies. Recent works focus on the fatigue behavior of 3D-printed specimens made of pure PLA and PLA reinforced with natural fillers such as pinewood, bamboo, and cork, manufactured by the FDM method. This research is aimed to answer the growing demand for biodegradable filaments. The fatigue study was done by tensile fatigue testing and a fracture surface in SEM. The other weakness recognized in the PLA-based biodegradable material was the fatigue life, defined as the number of cycles exceeding 50% of tensile strength from static tests.

The study showed that the addition of natural fillers like pinewood, bamboo, and cork had no serious influence on the fatigue life of PLA under almost the same status of loading. In cyclic loading ranging from 30% to 70%, there was an increment of viscoelastic behavior and permanent deformation. SEM analysis showed that there were problems with porosity and interlayer, though the interfacial bonding between PLA and the reinforcing natural fillers is strong.

Fouladi M.H, et al. (2020) enquired that the work presents the possible use of coconut waste as a bio-filler for biodegradable filaments, mainly for 3D printing applications. Readily available and sustainable, coconut waste can become one of the promising alternatives compared to traditional fillers. The present study was focused on the feasibility of incorporating coconut waste into biodegradable filaments by carrying out tests on mechanical and thermal stability and biodegradability. These results show that coconut waste-reinforced filaments are well capable for 3D printing applications and may turn out to become a sustainable and environmentally friendly solution for manufacturing everything.

Calì M, et al. (2020) investigated that represents the latest development in sustainable 3D printing through the manufacturing of bio-composite thermoplastic filaments. A blend of various biodegradable polymers along with natural fibers was used to prepare filaments much more environmentally friendly than conventional plastic filaments. In this work, if bio-based materials are used, the environmental impacts from 3D printing are reduced, maintaining good mechanical properties and printability. Besides, the feasibility of using various bio-composite

combinations that would test for strength, flexibility, and also biodegradability was considered. The study contributes to knowledge on the development of sustainable 3D printing technologies and improves the take-up of eco-friendly materials within manufacturing processes.

Lohar.D.V, et al. (2020) investigated on the application of waste bio-fillers in polylactic acid (PLA) composites and examines their mechanical and structural properties. It focuses on the incorporation of spent coffee grounds and spent tea leaves as sustainable fillers within PLA matrices. SCG and STL are rich in cellulose and lignin, which therefore offer an eco-friendly alternative for use as filling material within the matrix and at the same time help generate value from agricultural waste. Life-cycle considerations provide a window of opportunity to stimulate the bio- filler's ability to significantly influence the properties of the PLA composites.

The bio- fillers were hence compatibilized with PLA, and then different formulations of composites were obtained by melt blending these fillers along with PLA. The respective materials were analyzed to find their mechanical properties, flexibility, and overall structural integrity. The addition of SCG and STL improved some mechanical properties of the PLA, such as higher tensile strength and lower brittleness, both properties considered key in certain applications.

Sonia Dopico-García.M, et al. (2021) stated that material extrusion additive manufacturing is increasingly popular but requires new materials to expand its industrial applicability. This study compares the effects of two bio-fillers (lignin and spent coffee grounds (SCG)) in a biopolymer matrix, polylactic acid (PLA). The bio-fillers aim to enhance the sustainability of the resulting composites, tune their physical properties (rheology, thermal stability, mechanical resistance and water absorption) and improve 3D- printability by reducing the temperature at the nozzle. The composite with 15 wt.% SCG exhibited an elongation at break of 22.95% (vs. 8.42% for PLA), a printing temperature of 180C (vs. 215C for PLA) and a water absorption after 6 weeks immersion in water of 18.77 wt.% (vs. 5.04 wt.% of PLA), suggesting applications like hydroponic farming. Moreover, small amounts of SCG protected the composite against thermo-oxidative degradation during extrusion, while lignin enhanced the thermal stability of the composite.

Anjaneya Prasad Bannoth, et al. (2021) worked on fused deposition modeling (FDM), one among the most commonly used additive manufacturing (AM), techniques have been widely used in recent years to produce customized parts with intricate geometries, especially from thermoplastics. This method was limited in its ability to produce parts for industrial applications due to inferior properties and the poor quality of fabricated parts. Hence, researchers are being driven to discover novel materials that are viable for FDM in order to keep up with enormous demand for functional products. In the recent years, it is widely recognized that the emphasis was placed on the bio-based polymer composite matrices rather than conventional thermoplastics due to its vital advantages that aid in the replacement of synthetic and perilous materials. On this context, this review focuses on the recent advancements in FDM printing with biomaterials. Specifically, attempts have been made to investigate and provide nutshell of 3D printing of current bio-based nanocomposites which consist of either bio-derived filler or polymer matrices in order to make 3D printing sustainable. The effect of fillers on the filaments and FDM based products, evolution of novel characteristics of bio nanocomposites.

Victor Hugo M. Almeida, et al. (2021) invested about escalating global demand for polymer products and the consequent disposal challenge necessitate technological and sustainable solutions. Recent advances in the development of materials used in 3D printing equipment are described in this review, with a focus on new bio-composite materials. The investigation delves into bio-composites comprising PLA and its blends with other polymers, reinforced by plant fibers, with a particular focus on research conducted over the last five years. The information related to the raw materials' physical, chemical, and processing properties necessary for creating bio-composite filament and printed parts were summarized. The best results in terms of tensile and flexural strength were presented and discussed, signposting future research avenues and desirable objectives.

The findings elucidate that the inclusion of plant fibers led to a reduction in mechanical strength relative to pure PLA; however, when smaller particle sizes of plant fibers were added in volumes below 10%, it resulted in improved performance. Moreover, physical and/or chemical pretreatment of fibers, along with the isolation of cellulose fibrils, emerged as pivotal strategies for bolstering mechanical strengths. Noteworthy are the promising prospects presented by the incorporation of additives, while the refinement of printing parameters is key to

improving the tensile and flexural strength of printed components.

Husnu Yildirim Erbil, et al. (2021) summarized the formulation of PLA composites by incorporating a wide variety of additives to improve material performance for 3D printing applications. PLA is one of the most commonly used biodegradable polymers in extrusion-based additive manufacturing; however, in its pure state, PLA often suffers from several limitations with respect to brittle mechanical properties, low thermal stability, and limited durability. These shortfalls are preventing its use in various industrial and structural applications; therefore, characteristics related to it have to be improved. In relation to this, one of the most promising trends is associated with the admixing of bio-fillers made of natural fibers and other biological agents. These have a number of advantages. Addition of such fillers will improve the mechanical properties of PLA as well as provide some important eco-friendly manufacturing processes for sustainability associated with the 3D printing process. Besides, other benefits include possibly retaining PLA's biodegradable nature with the addition of the bio-filler- a nascent demand for greener technologies.

Boon Peng Chang, et al. (2021) concluded that graphite, graphene, and carbon nanotubes indeed owe their reputation to the outstanding performance they can develop when embedded into advanced composite materials. More recently, partially graphitic bio-sourced carbons have appeared in the form of a reinforcement that was at the same time effective, green, and low cost for polymers and bio-composites, including thermoplastics, thermosets, elastomers, and foams. Partially graphitic bio-sourced carbons derive from various biomass types through thermochemical conversion involving pyrolysis- a process conducted under controlled conditions with low oxygen. This technique thus allows for the property tuning of Bio-Composites, with respect to surface area, morphology, polarity, porosity, intrinsic modulus, and carbon content. Such engineered Bio Cs have been explored for multifarious applications, addressing material properties and sustainability improvements based on their specific attributes. This is a very meaningful step toward the introduction of renewable feedstocks within high- performance composite materials.

Roslan A. M, et al. (2022) concluded that aquarists have engaged in an argument for years about the significance of bio-filtration in both freshwater and marine aquariums. However, some bio-media filters on the market do not effectively breed bacteria in a closed aquatic environment, thus leading to poor filtration of ammonia. This can lead to inefficient water quality and poor health in aquatic life. Traditionally, bio-media filters have been produced by conventional manufacturing methods, which may not precisely meet the special requirements of increasing bacterial colonization and filtration efficiency. Further improved methods are needed in the design and production of bio-media filters to ensure more efficient bacterial growth and enhance filtration for cleaner and healthier aquatic environments. The advancement in the manufacturing techniques could be used to overcome such challenges, thus increasing the functionality of bio-filtration systems in disparate aquatic environments.

Lule Z.C, et al. (2022) carried out the present work, surface-treated coffee husks were combined with a polylactic acid matrix with the aim of formulating environmentally friendly composites with improved flame retardancy. High crystallinity and effective anti-dripping performance have characterized the resulting materials. The coffee husks, being lignocellulosic, consist of a complex macromolecular structure of cellulose, hemicellulose, and lignin. Spectroscopic analysis confirmed the success of phytic acid/amine silane treatment in bonding with the cellulose component of the CHs. It makes the treatment of the surface beneficial not only through improved interactions between CHs and PLA matrix but also by providing overall flame-retardant properties of the composites. In summary, incorporating such treated CHs into a PLA matrix really provides an effective way of producing sustainable materials with performance characteristics.

Mariateresa Lettieri, et al. (2022) researched on bio-fillers to improving mechanical performance in PLA foams. PLA is one of many biodegradable polymers, and its environmentally friendly properties are well documented; however, there are very few investigations concerned with improving its mechanical strength in applications requiring durable structural material. The presented work, therefore, discusses the reinforcement of PLA foams with bio- fillers for the enhancement of their compression modulus, which is essentially the ratio of compressive stress to resulting deformation. The study illustrates a remarkable rise in compression modulus upon the addition of bio-fillers, hence increasing the potential uses of PLA foams within various sustainable

applications. Improved mechanical properties will allow for a wide range of industrial applications, wherein these materials will include application usage from packaging and insulation to lightweight structural items. This work underlines the fact that the role of bio-fillers is not limited to mechanical reinforcement only in the case of PLA foams but is also accredited for rendering the material biodegradable, with a view of increasing the demand for environmentally friendly polymers for manufacturing purposes.

Marek Jalbrzykowski, et al. (2022) enquired the paper demonstrates an innovative process for thermoplastic bio-resorbable composite materials using polylactic acid (PLA) as a substrate. The approach alternates traditional biodegradable polymers with ground and dried waste plant material in the form of buckwheat husks and onion husks incorporated in a PLA matrix. The main purpose of addition of such fillers of a plant origin is the increase in the level of environment friendliness and functionality. The processing of such composites is described in the paper, along with the adopted methodologies for the better integration of plant waste and PLA. It also explores possible improvements compared to traditional biodegradable materials, considering improved mechanical properties and a reduction in environmental impact. In the approach presented here, agricultural by-products are used to solve waste management problems and develop a more sustainable route to bioresorbable material.

Shunmugasundaram.M, et al. (2022) explained about additive Manufacturing- usually maintained by its synonym 3D printing-is a revolutionary manufacturing concept. With the help of dedicated apparatus, three-dimensional objects are made by successively adding the intended material, usually in layers. For AM technologies, which include several variants, this is in contrast to traditional subtractive methods of manufacture, where an object is cut from a solid block of material. In AM, an object is built from scratch according to digital models. These layers are carefully applied to make complex geometries and intricate designs that could hardly be achievable, or very challenging with conventional techniques. The technology allows for greater design flexibility, rapid prototyping, and customization, making it highly suitable for applications that range from industrial parts to medical implants. Additive manufacturing, aided by technology, augments the efficiency of processes by making use of a wide variety of materials such as plastics, metals, and composites, and thus opens the door for innovative solutions in many industries.

Zhao et al. (2022) investigated the incorporation of natural fillers into PLA for 3D printing applications. Their study focused on various agricultural waste products, including fruit seeds, as potential reinforcing agents. The researchers found that incorporating finely ground custard apple seeds into PLA improved the material's tensile strength and impact resistance. The optimal concentration of custard apple seed powder was determined to be 5% by weight, beyond which the mechanical properties began to decline. The study also examined the thermal properties of the blended material, noting an increase in crystallization temperature and a slight decrease in glass transition temperature. The researchers attributed these changes to the nucleating effect of the seed particles and the increased mobility of polymer chains. The study concluded that custard apple seeds, when properly processed and incorporated, could serve as an effective and environmentally friendly filler for PLA in 3D printing applications, potentially reducing material costs and improving sustainability.

Biyou Peng, et al. (2022) studied on development of biological scaffolds with complex geometries and tunable internal structures is indeed a great achievement in tissue engineering. Among the many available techniques for fabricating scaffolds, FDM has been popular for its simplicity of operation, low cost in use, and relatively inexpensive apparatus. Using FDM, layer-on-layer scaffolds can be built up with high accuracy to provide complex geometries and internal architectures that may be designed for optimum growth and regeneration in a tissue. These applications are highly feasible, given the commercial availability of this technology, coupled with its economic advantages, for the fabrication of scaffolds, whose properties can be specially adapted for biological applications. Once more, the use of the FDM method allows for inventing scaffolds by researchers and clinicians in a more resourceful manner, with geometrical structure that allows the integration and functionality of the engineered tissues, therefore one step further toward personalized and effective solutions in tissue engineering.

Sahar Sultan, et al. (2022) explained biologically based and patient-specific three-dimensional scaffolds are promising approaches to developing BTE approaches for critical-sized bone defects. The work described in this paper uses a composite filament prepared by using poly lactic acid (PLA) with 45S5 bio-glass (BG) for 3D printing

of scaffolds specifically designed for bone tissue regeneration. PLA is a biodegradable polymer, whereas 45S5 BG exhibits bioactive properties, including the enhancement of bone formation. Therefore, a composite filament comprising these two would thus enable the fabrication of scaffolds with specified mechanical and biological properties that could facilitate the healing and growth of bones.

Shrutika Sharma, et al. (2022) investigated that the PLA-based materials made by 3D printing are found to be biocompatible, porous, and bioresorbable substitutes to metallic implants. However, in most cases, PLA usually possesses low mechanical strength, and this limits its use within biomedical areas. The present study deals with the surface modification of these materials using polydopamine via the direct immersion coating technique. In this research work, the response surface methodology was employed to investigate the influence of such input process parameters as infill density, immersion time, shaker speed, and coating solution concentration on the mechanical properties. Therefore, this work optimizes those parameters in an effort to enhance the mechanical properties of PLA-based implants to be used in different biomedical applications for the realization of effective alternatives to the traditional metallic implants.

Iris K. M. YuOi Yee ChanQiaozhi Zhan, et al. (2023) explored food processing by-products are waste materials but are obtained in large quantities, varied, and economical, besides enabling the provision of a basis for developing a sustainable composite material for a wide application range. This work explores the possibilities of using such by-products as fillers during the fabrication of biomass/ (polylactic acid) PLA composites for 3D printing. SCG and STL are both good sources of cellulose, hemicellulose, and lignin, which would likely enhance the PLA mechanical properties and sustainability. These composites were prepared by treating SCG and STL first with treatments that improve their compatibility with PLA. The treated by products were then compounded with PLA to produce composite filaments that may be considered suitable for 3D printing. The latter not only uses waste material but also reduces the need for virgin resources. The printability and the structural integrity of resultant composites were assessed in the current study. The properties of PLA matrices containing SCG and STL were improved compared to those containing pure PLA, which shows their potential as high-performance, sustainable fillers.

Patrizia Tassinari, et al. (2023) presented work that demonstrates the suitability of wastes deriving from wheat milling process as bio-filler in 3D printing materials. Upon the design and optimization of the whole production process, a 3D printable bio-composite filament was obtained and characterized. The designed material showed some variations in terms of thermal properties when compared to the reference material: that is, a slight decrease in thermal stability, a reduction of CP value, and a strong nucleating effect of the wheat grain waste. Besides these results, the main properties of pure PLA are preserved and, so, the significance of these bio-composites was confirmed with the prosecution of further studies, such as 3D printing tests and designing of new bio-composite formulations.

Dong, et al. (2023) stated the work focuses on the development of 3D printable bio-composite filaments through the reinforcement of polylactic acid with cellulose nanofibrils extracted from forestry waste. Their addition to PLA matrices significantly improves the mechanical performances of the filaments. In using cellulose nanofibrils a byproduct of forestry operations-the research provides not only value addition to PLA but also sustainability by repurposing environmental wastes into value-added products. These bio-composite filaments therefore exhibit improved strength and rigidity compared to standard PLA, demonstrating effectively the efficiency of using eco-friendly feedstock in advanced manufacturing. This has pointed out the probable use of natural fibers in 3D printing materials to attain superior mechanical performance with ecological benefit and innovations within the additive manufacturing arena.

Madhan N. R, et al. (2023) stated the reason of its durability and versatility, polypropylene finds quite an extended application in various industries, biodegrade and is associated with tough environmental challenges. Recyclable polypropylene materials have to be "closed loop" to return the material to a product-to-product cycle such that the material is returned for reprocessing, in order for the material to be retrieved and used again to avoid waste and conserve resources. All of this will decrease the demand for virgin materials, lower the level of pollution, and give a chance to take part in the development of a more circular economy. Enhancing polypropylene recycling

techniques and increasing the rate of polypropylene recovery mitigate some of the environmental concern and support the target for long-term sustainability.

Al Mazedur Rahman, et al. (2023) concluded the transformation of biowaste derived from agriculture into a number of added value materials, such as powders, fibers, filaments, among others, for Additive Manufacturing techniques. A review concerning the development of new materials from such biowastes is presented in this paper, summarizing the actual literature on their application in 3D printing and other additive procedures. It addresses and scrutinizes the processing and utilization of these materials while appraising the properties, performance, and potential benefits. This technique will be put forward for the first time as an additive manufacturing technique with the use of agricultural by-products that present an environmentally friendly option over conventional materials with the potential benefits of waste reduction and promotion of resource efficiency. The aim of the review is to consolidate knowledge, show advances in material development, and discuss implications for more eco- friendly manufacturing practices as a furtherance to the ongoing evolution of sustainable technologies within the field.

Chunhua Luo, et al. (2023) stated that PLA is one of the most abundant bio- polymers derived in general from renewable crops, such as corn and rice. Interest in polylactide for applications in 3D printing has caused an increased interest in the need for new functional materials based on PLA. Traditional methods for the preparation of such functional printable materials have been up until now time- consuming or environmentally harmful. Most of these conventional routes include cumbersome procedures or the use of risky chemicals, which make PLA less "green." In this light, much interest has been demonstrated in developing a more efficient and greener route for PLA functionalization that is associated with as little environmental impact as possible. This shift is supposed to allow ways in improving the applicability and sustainability of PLA-based materials in order to develop innovative, more responsible uses in 3D printing.

Andrea Aguilar-Sánchez, et al. (2023) addressing the need for multi-functional, robust, reusable, high-flux filters for sustainable water treatment, this work developed fully biobased and biodegradable water purification filters using 3D printing, specifically FDM. In this work, the fabricated filters were made from PLA- based composites reinforced with homogenously dispersed TEMPO-oxidized cellulose nanofibers or chitin nanofibers. This four-step process involved melt blending of PLA with the nanofibers, followed by pelletizing via TIPS, freeze- drying of the pellets into nanofibrous membranes, and finally single-screw extrusion into 3D printing filaments. The approach ensures that filters are both green and highly efficient, therefore offering superior performance for water purification applications. The mechanical strength and filtration efficiency of the final printed filters could be enhanced through the incorporation of nanofibers into the PLA matrix.

Senthil.S, et al. (2023) concluded that non-biodegradable polypropylene also finds common use in the automotive, paint, and consumer product industries. Therefore, recycling it is a necessity regarding the issues of sustainability. In cases when it was being used as a 3D filament, problems related to warping are leading to limited research in this area. This study attempts to overcome these issues by using tamarind fruit shell powder as a filler in both virgin and recycled polypropylene to create a 3D composite filament. The inclusion of TFSP was conducted to nullify the warping issues of the 3D printing of polypropylene. This research will study the effects of this reinforcement with respect to filament performance in order to improve print quality and reliability. The results of such a study may provide a partial solution to warping issues and, therefore, contribute to more effective use and sustainability of polypropylene in additive manufacturing.

Rdriguez, et al. (2023) conducted a comprehensive study on the effect of various natural fillers, including custard apple seeds, on the mechanical and thermal properties of PLA for 3D printing applications. The research focused on comparing the performance of different fruit seed powders and their impact on print quality and material properties. The team found that custard apple seed powder, when incorporated at 3-5% by weight, provided a balance of improved mechanical properties and good printability. The blended material showed a 15% increase in tensile strength and a 20% improvement in impact resistance compared to pure PLA. Thermal analysis revealed that the addition of custard apple seed powder increased the material's crystallinity, potentially improving its heat resistance. The study also examined the biodegradability of the blended material, noting that the incorporation of custard apple seed powder did not significantly affect the biodegradation rate of PLA.

Abu Naser Md Ahsanul Haque, et al. (2023) stated about material Extrusion- based Additive Manufacturing (MEX-AM) is rapidly becoming a popular, easy, 'green', and safe process with minimal generated waste worldwide. Ease of operation has made the process extremely popular industrially as well as in household applications. Recently, much interest has been developed in PCL- based composites due to their increased biodegradability in MEX. Printing of PCL- based composite materials is achieved at lower temperatures compared to most commercial filaments of ABS and PLA, hence the process is more energy- efficient. Such benefits, in turn, contribute not only to reduced energy use but also to the growing emphasis on environmentally friendly manufacturing. The PCL- based composite material can provide benefits for industries in sustainability and cost efficiency and move capabilities and applications of additive manufacturing technology forward.

José Miguel Ferri, et al. (2023) explored the present paper studies the effect of the addition of various types of silk fillers, together with a melanin corn oil- based environmentally friendly plasticizer, on the improvement in both the mechanical and thermal behavior of PLA composites. PLA composites with 10 wt.% MCO and 0.5 phr CS, SFM, and SFN were prepared with the help of melt extrusion and subsequent injection molding. Thus, the PLA formulation with 10wt% MCO and 0.5 g of CS per one hundred grams of composite showed the most significant improvement in mechanical ductility, approaching about a 1400% increase in elongation at break with respect to pure PLA. The DSC results show a difference in the glass transition temperature of the material with and without a silk filler; the difference is 2°C.

Sergio Martín-Béjar, et al. (2024) carried out the work at hand was done to study the effects of cellulose, coffee, and flax as natural fiber reinforcements on the fatigue resistance and dimensional stability of PLA in ME processing. PLA is one of the most adopted biodegradable polymers by three-dimensional printing, but a series of mechanical limitations, such as poor fatigue resistance and dimensional stability, usually limit its industrial applications. These properties are improved by the addition of natural fibers into the PLA matrix, which give better reinforcement. In this work, the addition of such bio-fillers enhances the fatigue life of PLA significantly by improving its resistance to cyclic loading. Additionally, the fibers improve dimensional stability of the material by reducing shrinkage and deformation upon printing. These improvements enable the application of PLA composite materials in higher strength applications without sacrificing accuracy. In general, the approach of adding natural fibers to PLA can be seen as a promising means to overcome its mechanical limitations when it comes to material extrusion technologies.

Lago Silva da Cruz, et al. (2024) concluded with the aid of cellulose fibers obtained from cocoa husks, this study represents an effort to explore their potential as bio-fillers in polylactic acid (PLA) composites with emphasis on their mechanical properties and biodegradability. Cocoa husks, which are by-products of cocoa processing, are about 30% cellulose by weight, and therefore are a potential source for low-cost, renewable filler for enhancing the mechanical properties of PLA, which is a biodegradable thermoplastic. Cellulose fibers were incorporated into PLA to generate composite materials and mechanically tested to evaluate performance. Tensile strength evaluation was conducted to estimate how cocoa husks would affect the load-bearing capacity and structural integrity of the composites. In consideration of the environmental impacts of PLA-cocoa husk composites, the biodegradability of the formed composites was analyzed to observe how the introduction of natural fibers will impact the environmental impacts of the material. The noticed improvements in tensile strength of PLA- cocoa husk composites over pure PLA and durability demonstrated the intrinsic values of the filler in the mechanical properties of the composite.

Sakthi Balan.G, et al. (2024) studied on how incorporation of additives into polymer filaments used in 3D printing via material extrusion can modify the properties. It looks into the amount that can be considered optimum, additives that can be incorporated into the polymers to give desirable property modifications while considering the beneficial and detrimental effects of the same on the printed parts. The overall tendency of the review portrays the different forms of additives and their effect on the mechanical, thermal, and structural properties of polymer filaments. In addition, it discusses how incorporation of such changes affect the final performance as well as quality of the components manufactured using a 3D printer. This review attempts to draw insights from current research and practical findings on guiding more effective and efficient 3D printing practices in terms of how to

maximize benefits of using additives and minimizing potential drawbacks.

Madheswaran Subramaniyan, et al. (2024) presented the optimization of the bio-composite material through additive manufacturing for the development of customized implants. This paper reports on works exploring the use of polylactic acid as a matrix with different weight percentages of hydroxyapatite reinforcement in the composites. The structural, mechanical, and thermal properties of 3D- printed bio-composites are evaluated herein, and in vitro characterization is carried out with a view to their usefulness for in vivo implant applications. The properties so derived would be analyzed with the intention of making these composites performance- and function-improving for the research, and hence providing improvements in implant customizability and effectiveness. The developed findings will add to the stream of research on advancing patient-specific implant materials that could synergize both sets of properties coming from PLA and HA in the procedure of additive manufacturing.

Abhijit Bhowmik, et al. (2024) reported that Filler materials are used to develop and optimize composite materials and hence have been in increasing demand due to new properties of enhanced goods in relation to conventional material. This chapter will peek into these fillers and introduce their functions, properties, and roles in composite materials. Some of the emerging trends in filler technology involve the development of sustainable and eco-friendly fillers, and nanoscale fillers. These innovations all focus on better composites performance and an enhanced environmental composite foot print. These issues have been targeted in the current chapter to provide insight into the current status, real challenges, and future trends of filler technology in the field of composite material applications, focusing on an advantageous balance for composites performances and composites sustainability.

Abdelghani Lakhdar, et al. (2024) studied on the biomaterials enter into 3D printing, one of those pivotal developments whose ripples will continue to extend well into medicine, biomedical research, and custom manufacturing. Such integration allows for the fabrication of highly specialized and personalized solutions, such as tailored implants and prosthetics, which can be precisely matched to individual patient needs. Biomaterials in medicine allow the elaboration of complicated tissue structures and scaffolds, capable of supporting tissue regeneration and repair. Biomedical research, therefore, benefits from the capacity to fabricate personalized models for the study of disease mechanisms and testing new treatments. Biomaterials in personalized manufacturing further allow the creation of innovative components with enhanced functionality and performances. It is the combination of biomaterials with 3D printing technology that creates new opportunities for research and applications, pushing forward prospects for personalized healthcare and advanced manufacturing techniques.

Cristina Vălean, et al. (2024) concluded that the Fused Deposition Modeling remains today probably the easiest access additive manufacturing technology because of its combination of low cost and ease of use. The method works in such a way that the rather simple design based on thermoplastic polymers lays down in a layer-by-layer fashion for developing three-dimensional objects. Beyond that, which really helps drive the cost even further, the cost is extremely low due to the price of these thermoplastic materials and their ready availability. This makes it suitable for both the hobbyist and professional. Be that as it may, the ease of operation and relatively lower operating costs have democratized 3D print technology through FDM machines with broad adoption across various industries for example, rapid prototyping, classes in education, and for limited production. FDM is one of the fastest and most economical ways to produce prototypes, using off-the-shelf thermoplastics to model designs or prototypes of needed geometries, making it a favorite in the additive manufacturing arena.

Anahita Homavand, et al. (2024) studied on the recent statistics indicate a rise in the production of eggs over recent decades, therefore increasing the global biomass of eggshells. In reality, eggshells represent underutilized bio-waste. There are many known uses of waste eggshells, which are referred to as WEGs, including food additives for humans and animals. WEGs can also be utilized as an amendment in soil as well as in cosmetic formulations. Even in application fields like catalysts, sorbents, and polymer composite fillers. Applications of WEGs for various uses epitomize the huge potential of these wastes to different industries and at the same time offer a very environmentally friendly way to handle this rich co-product. Industries are in the process of reducing

waste, enhancing the efficiency of resources, and working toward environmentally friendly materials through research and development by finding new applications for eggshell waste.

Filippo Biagi, et al. (2024) carried out present work, grape seeds, wine lees, and grape pomace represent the most common winery by-products tested as bio-filler agents. These are combined with two different biopolymer matrices, namely poly (butylene adipate-co- terephthalate) and polybutylene succinate, for the production of fully bio-based composite materials. The present work aims at establishing how such winery by- products can be used in enhancing the properties of biopolymers, considering the resulting material performance and sustainability. In this way, using natural fillers in this research can come up with composites, which will be environmentally friendly and at the same time efficient in different application areas. This also calls for the use of agricultural waste and developmental eco-sensitive materials.

Shiva Aley Acharjee, et al. (2024) enquired such biomaterials, PHA or more precisely polyhydroxybutyrate is a real alternative to the conventional petroleum- derived plastics due to their total biodegradability. It is also biocompatible with tissues and organs and non-toxic. Consequently, PHAs could be widely used in various fields such as food packaging, agriculture, medicine, etc. However, there are some serious drawbacks to such promising perspectives due to their quality problems. PHAs generally suffer from several disadvantages: high production cost, brittleness, poor heat stability, and unsatisfactory mechanical properties. The various issues presented can limit their practical use and scalability. In relation to this, the overcoming of such limitations will be important in their development from a niche solution to a mainstream material. Overcoming such challenges is necessary in enhancing research and development that aims at improving performance and cost for these PHAs so as to further open their full potential in sustainable material applications.

Luis C. Rodriguez-Pacheco, et al. (2024) concluded that 3D printing, also known as AM, AM, has provided a revolution in modern manufacturing through the ability to produce geometrically sophisticated structures in a wide range of industries. This research paper proposes a novel approach through the addition of ZCB precursors to PLA for the purpose of creating composite filaments used in FDM 3D printing. Upon laser irradiation at high powers, these filaments would then undergo a surface transformation into ZnO. To confirm this transformation, the thermal analysis was performed using techniques such as TGA-DSC and FTIR. These analyses confirmed that, during the process of thermal decomposition, ZCB ($[\text{ZnCO}_3]_2 \cdot [\text{Zn}(\text{OH})_2]_3$) was transformed to ZnO

III. AIM AND SCOPE

3.1 AIM OF THE PROJECT

The aim of the project is to develop and analyze a biodegradable 3D printing filament by incorporating CASP into PLA. This research tries to conceptualize, develop, and carefully examine a novel group of completely biodegradable composite materials by purposefully incorporating derivatives of custard apple seeds in Polylactic Acid (PLA) matrices. The study covers the entire developmental path of these new biomaterials, starting with the extraction and purification of natural particulate material from Sapodilla fruit seeds—being a copious agricultural waste of high untapped potential. With advanced materials engineering strategies, this work seeks to unravel the complex physicochemical interplay at the interface between plant-based fillers and synthetic biopolymer architectures during precision extrusion-based processing procedures. The research will utilize cutting-edge analytical techniques to measure the revolutionary impacts on mechanical toughness, heat response, shape characteristics, and processing rheology caused by this bio-composite composition.

The study aims at developing elementary relations between microscopic architecture and large-scale performance traits and explaining how the mechanisms underlying crop derivatives are beneficial to the functional properties of the polymer. Specific focus will be directed toward the establishment of specific mathematical relationships among key variables such as filler concentration gradients, particle size distributions, surface treatments, and process parameters toward setting optimum formulation requirements for high- performance 3D printing filament production. Through the development of full manufacturing protocols and composition specifications, the research shall create a science basis allowing the systematic conversion of agricultural residues to value-added engineering materials with superior functional characteristics.

This research further hopes to provide answers to serious sustainability issues faced by today's materials science

with pioneering green alternative materials to petrochemical polymers without performance trade-offs. Through controlled discovery of structure-property-processing linkages, the work will build predictive models for facilitating rational design of bio-composite systems with predetermined property specifications. Above technical description, the research includes thorough sustainability evaluation by life-cycle analysis procedures, setting quantitative targets for environmental footprint lowering in contrast to normal materials. The final aim goes beyond simple laboratory proof, with a target to create commercially successful bio-composite formulations suitable for industrial application, thus fostering the move toward circular economy practices in high-level manufacturing uses.

3.2 OPTIMIZATION OF AGRICULTURAL FILLER PROCESSING AND CHARACTERIZATION

The systematic conversion of custard apple seed material from farm waste to engineered filler represents a core element of this research program, requiring the creation of specialized processing techniques optimized for biopolymer compatibility. The study will determine accurate protocols controlling key processing variables such as thermal treatment regimens, mechanical comminution parameters, and classification systems to produce filler populations with controlled dimensional properties and surface characteristics. Multidimensional particle characterization through laser diffraction analysis, gas adsorption, and computational morphology testing will define complete particle profiles including size distribution, shape factors, aspect ratios, and surface topography. Surface chemical characterization through X-ray photoelectron spectroscopy, infrared spectroscopic mapping, and state-of-the-art microscopy methods will define the spatial distribution of functional groups that affect matrix compatibility. Compositional characterization by thermochemical analysis, chromatographic fractionation, and spectroscopic detection will measure proportions of structural biopolymers, extractives, and bioactive substances possibly adding to composite properties improvement. Research will also examine chemical and physical modification routes involving silane reactions, alkaline treatment, and plasma activation to tailor control over surface energy features with systematic adjustments of adhesion property traits at interfaces of hydrophilic botanical reinforcement material and the relatively hydrophobic PLA matrix. This complete characterization sets critical foundation knowledge that guides follow-up composite development activities.

3.3 ADVANCED METHODS IN COMPOSITE FORMULATION AND PROCESS OPTIMIZATION

Successful integration of botanical fillers into synthetic polymer matrices is an interdisciplinary engineering problem that involves systematic optimization of processing techniques to attain uniform dispersion and avoid thermal degradation of temperature-sensitive natural components. This research stage will systematically compare several compounding methods such as high-shear extrusion systems with tailored screw geometries, controlled-atmosphere mixing chambers, and solvent-assisted pre-dispersion methods to obtain maximum microstructural ordering.

Experimental design methods will create mathematical correlations between key processing variables such as thermal profiles, shear rates, residence times, and atmospheric conditions and resultant composite microstructure, measured by advanced microscopic analysis and tomographic reconstruction. Compatibility improvement strategies using functionalized coupling agents, reactive extrusion processes, and grafting methods will be rigorously tested for effectiveness in enhancing interfacial bonding properties.

Real-time rheological measurements during compounding processes will yield instant feedback on melt behavior dynamics, enabling adaptive process control to ensure optimal flow properties during production processes. Post-processing characterization using electron microscopy, energy-dispersive spectroscopy, and high-resolution tomographic imaging will measure key microstructural parameters such as dispersion homogeneity, agglomeration tendencies, void formation.

3.4 DETAILED MECHANICAL PERFORMANCE EVALUATION

This research will utilize systematic mechanical characterization techniques consistent with global testing protocols to determine quantitative relationships among composite formulation parameters and resultant performance attributes over a range of loading conditions. Uniaxial tensile testing over a range of strain rates and environmental conditions will describe basic mechanical properties such as elastic modulus, yield strength, ultimate tensile strength, and elongation capability, while concurrently examining time-dependent viscoelastic response essential to engineering applications.

Flexural performance characterization using standardized beam deformation testing techniques will measure

bending resistance and stiffness properties under distributed loading conditions, whereas impact testing using instrumented pendulum and falling-weight methods will evaluate energy absorption capability and fracture toughness under dynamic loading conditions representative of actual impact incidents. Surface and subsurface deformation resistance will be assessed by complementary hardness evaluation methods across macro, micro, and nanoscale indentation techniques to create complete resistance profiles across multiple length scales applicable to different application needs.

Dynamic mechanical analysis characterization will create temperature-dependent viscoelastic behavior profiles, and time-dependent deformation testing will measure creep resistance and stress relaxation properties critical for dimensional stability in structural applications. Fractographic analysis using high-resolution microscopy will clarify failure initiation mechanisms and crack propagation pathways, establishing direct correlations between microstructural characteristics and macroscopic mechanical performance.

3.5 THERMAL BEHAVIOR AND PROCESSING RHEOLOGY INVESTIGATION

The research program involves advanced thermal characterization using complementary analytical techniques such as differential scanning calorimetry, thermogravimetric analysis, and thermomechanical evaluation to define quantitative correlations between composite composition and key thermal transitions controlling both processing behavior and application performance. Crystallization research using isothermal and non-isothermal procedures will explore possible nucleation effects caused by plant-based fillers, focusing on crystalline morphology, crystal size distribution, and crystallization kinetics that could lead to improved mechanical properties.

Thermal stability characterization under programmed heating at controlled atmospheric conditions will determine thermal stability, decomposition kinetics, and char-forming tendencies, while thermal conductivity characterization will measure heat transfer properties of interest to both processing conditions and thermal management in functional applications. Extensive rheological analysis using rotational, capillary, and extensional techniques will determine flow behavior profiles across the entire deformation regime experienced in processing operations, from low-strain viscoelastic response to high-shear non-Newtonian behavior typical of constrained flow conditions. Time-dependent rheological characteristics such as thixotropic response, development of melt strength, and viscosity stability on prolonged thermal exposure will define processing toughness critical to commercialization.

Extensional rheology testing will quantify resistance to filament drawing processes essential for reproducible extrusion processing, and pressure-driven flow characterization will duplicate conditions for nozzle extrusion in additive manufacturing processes. This combined rheological characterization will define processing windows and parameter optimization approaches for filament production as well as subsequent printing processes.

3.6 ADDITIVE MANUFACTURING OPTIMIZATION AND PRINT QUALITY EVALUATION

Systematic optimization of formulation for additive manufacturing use is a prime research goal, involving critical balance between increased mechanical performance and retained processability features necessary for uniform extrusion operations. Incremental filler loading investigations over concentration ranges from trace addition to highly filled systems will determine complete property- concentration relationships with specific focus on determining threshold concentrations above which processing difficulties exceed performance advantages. Specialty filament production trials using precision extrusion equipment with sophisticated monitoring features will assess key quality factors such as dimensional uniformity, surface finish, mechanical integrity, and moisture sensitivity over a range of formulations and processing conditions. Systematic printing parameter optimization using statistical experimental design techniques will define mathematical correlations between key variables such as extrusion temperature, platform conditions, feed rates, layer geometries, and cooling strategies and resultant print quality measures such as dimensional accuracy, surface finish, and interlayer adhesion strength. Dedicated test artifacts that are specifically designed to test particular printing capabilities will assess geometric fidelity, feature resolution, overhang capability, and bridging ability for different composite formulations.

Mechanical performance characterization of printed structures will provide correlations between processing conditions and resulting functional properties, and possibly indicate synergistic enhancement opportunities through optimized printing. This extensive characterization will provide formulation specifications and processing guidelines particularly suited for additive manufacturing applications with these new bio-composite materials.

3.7 ENVIRONMENTAL FOOTPRINT AND BIODEGRADABILITY OF PLA WITH CASP

This research area includes holistic evaluation of environmental performance throughout the entire material life cycle, from agricultural byproduct procurement to processing, functional use, and final biodegradation. Quantitative biodegradability testing using controlled composting conditions, soil burial tests, and enzymatic degradation methods will determine quantitative degradation kinetics and mechanism identification for different end-of-life conditions. Molecular weight analysis by chromatographic methods will monitor polymer chain scission in degradation processes, and spectroscopic examination will detect intermediate compounds and final degradation products to ensure compatibility with the environment. Ecotoxicological testing of degradation products on standardized aquatic and terrestrial test organisms will confirm environmental safety during the entire material life cycle.

Full life cycle evaluation conforming to standardized protocols will measure environmental footprint profiles on a range of sustainability indicators such as carbon footprint, energy use, water usage, and emissions of chemicals, providing direct comparative evaluation against traditional petroleum-based alternatives. Farming sustainability evaluation will analyze the environmental consequences of byproduct usage in terms of sustainable agriculture, while economic feasibility determination will determine business potential through advanced cost modeling and market forecasting. These multi-dimensional sustainability assessments will provide quantitative indicators showing the environmental benefits of agricultural waste valorization strategies in a circular bioeconomy context, potentially setting policy guidelines for large-scale implementation of similar strategies in various material categories.

This all-encompassing research program, combining various scientific disciplines ranging from materials science and polymer engineering to agricultural technology and sustainability assessment, seeks to create a paradigm-shifting strategy for biodegradable composite development through agricultural waste valorization. Through the focused examination of complex interrelationships involving material composition, processing technique, microstructural formation, and macroscopic performance, this research will determine design considerations and manufacturing standards that can apply not just to custard apple seed composites but possibly also to various farm byproducts whose similar technological reassessment is expected. This developing knowledge base will drive the future towards genuinely circular material systems for advanced manufacturing processes, while overcoming polymer sustainability challenges and agricultural waste management opportunities on the way.

IV. MATERIALS AND METHODOLOGY

4.1 MATERIALS AND EQUIPMENT

4.1.1 Polylactic Acid (PLA)

Polylactic Acid, also referred to as PLA, is a biodegradable thermoplastic from renewable resources such as cornstarch and sugarcane. With physical properties of having a density close to 1.24 g/cm^3 , melting temperatures within the range of $150\text{--}180^\circ\text{C}$, and glass transition around about $60\text{--}65^\circ\text{C}$, PLA yields excellent rigidity and tensile qualities[33]. In this project, PLA is the basic matrix material, chosen for its ability to integrate without a hitch into FDM printing technology. The eco-friendly alternative to petroleum-derived polymers has outstanding mechanical toughness and thermal resistance—properties key to additive manufacturing use. Either raw pellets suitable for bespoke extrusion processes or pre-fabricated filaments suitable for use in direct printing can be acquired as the raw material[34].



Figure: 4.1: PLA Pellets

4.1.2 Custard Apple Seed Powder (Filler)

Seeds of *Annona squamosa* (custard apple) are converted into a precious bio- filler by a multi-step processing procedure. This is initiated with precise seed extraction from the fruit, followed by rigorous dehydration either in natural sunlight or controlled oven conditions, and ending with mechanical pulverization to produce fine particulate matter[35]. Adding this natural filler into the composite provides many benefits: faster decomposition properties, reduced dependence on virgin PLA (increased sustainability values), possible strengthening of structural properties such as impact resistance, and cost savings versus engineered fillers. The addition can take many seed preparations, from lightly processed dried samples to thermally processed (roasted) types with unique performance characteristics, to extremely fine powder assuring best dispersion in the polymer matrix[36].



Figure: 4.2: Custard Apple Seed Powder

4.1.3 Dichloromethane (DCM)

Dichloromethane, also shortened to DCM, is a colorless volatile liquid heavily used as a solvent in industry and laboratory settings. It has a density of approximately 1.33 g/cm^3 , a low boiling point of roughly 39.6°C , and a melting point that is roughly -96.7°C , which effectively dissolves many organic compounds[37]. DCM is selected as the main solvent in this research because of its high solvency and high evaporation rate. The chlorinated solvent is a key compound in applications where effective dissolution and fast drying are needed, hence its role in material preparation and chemical processes. DCM can be found on the market as pure liquid for precision applications or as formulated mixtures of solvents specifically designed for certain industrial applications[38].

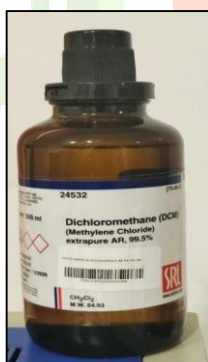


Figure: 4.3: Dichloromethane

4.1.4 3D Printing Filament Extruder

The filament extrusion system represents specialized equipment engineered to thermally process and blend PLA with custard apple seed additives, subsequently forming continuous strands suitable for additive manufacturing applications. This device accomplishes a number of important tasks: thermal treatment of PLA granules to produce the correct flow properties, complete blending of seed particulates during the molten polymer, accurate dimensional control upon extrusion (usually producing 1.75mm or 2.85mm diameter filaments as required by the printer), and controlled cooling with spooling mechanisms for ease of storage and handling for subsequent fabrication processes[39].

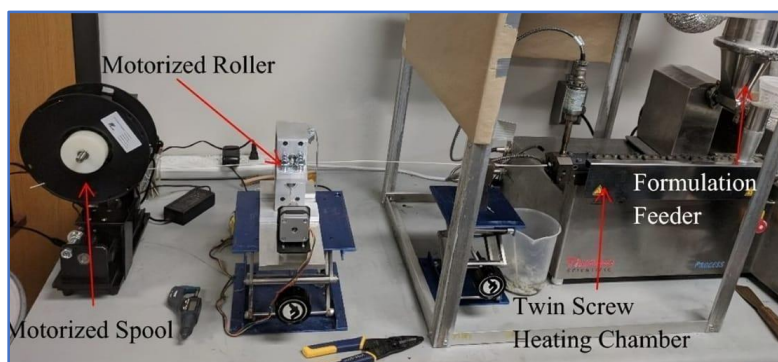


Figure: 4.4: Filament Extruder

4.1.5 3D Printer (Fused Deposition Modeling, FDM)

The FDM printing platform is the terminal device in the fabrication process, with the PLA-custard apple seed composite fabricated through the customized development process. The operating methodology includes inserting the specially developed filament into the printer system, with the thermal components raising the temperature of the material to its peak deposition stage[40]. The print head subsequently deliberately dispenses the flowing composite into programmed paths, creating successive layers that harden upon cooling to form the object as designed. This additive manufacturing method has several advantages for application: accessibility and affordability on different implementation scales, inherent compatibility with PLA-based compositions such as bio-composites, and production of environmentally friendly products when using renewable resource- derived materials supplemented with natural agricultural byproducts such as custard apple seed powder[41].



Figure: 4.5: 3D Printer

Table 4.2: Properties of Materials

Property	Custard Apple Seed Powder	Polylactic Acid (PLA)
Source	Powder made from dried custard apple (<i>Annona squamosa</i>) seed grinds.	Obtained from renewable materials such as cornstarch or sugarcane by polymerization.
Physical Form	Powder with mixed particle size, depending on method of processing	Available in pellet or filament form for 3D printing and extrusion.
Color & Appearance	Brown to dark brown color, varying with process (fresh, dried, roasted).	Translucent to white in natural form; can be colored with additives.
Density	Lower density than PLA; varying with particle size.	~1.24 g/cm ³ , with good mechanical strength and rigidity.

Thermal Stability	Moderate thermal resistance, prone to degradation at elevated temperatures.	Glass transition temperature of ~60-65°C, melting temperature of ~150-180°C.
Mechanical Strength	Poor intrinsic mechanical strength but enhances the impact resistance of PLA when applied as a filler.	High tensile strength and stiffness, with good suitability for structural applications.
Biodegradability	Naturally biodegradable owing to organic content; breaks down more quickly in soil conditions.	Biodegradable under industrial composting but slowly degrades in nature.
Chemical Composition	High in fibers, antioxidants, proteins, and essential oils, promoting sustainability.	Made up of Lactic Acid Monomers that create a thermoplastic polymer structure.
Water Absorption	Increased water absorption owing to organic content, which can influence stability.	Low water uptake, which makes it less susceptible to moisture degradation.
Adhesion to PLA	Needs coupling agents for improved adhesion with PLA matrix.	Tends to stick to itself and other thermoplastics naturally but needs to be modified for composite use.
Processing Compatibility	Needs drying and surface treatment prior to mixture with PLA to ensure even dispersion.	Processed easily through extrusion, injection molding, and 3D printing.
Environmental Impact	Completely biodegradable and decreases dependence on synthetic filler, promoting eco-friendliness.	Eco-friendly compared to petroleum-based plastics, but requires controlled conditions for degradation.
Applications	Utilized as a bio-filler in composite materials, biodegradable packaging, and natural reinforcement.	Commonly used in 3D printing, disposable packaging, medical implants, and bioplastics.

4.2 METHODOLOGY

4.1.6 Fabrication Process of Pla–Custard Apple Seed Composite Filament

The process starts by measuring accurately and mixing polylactic acid (PLA) pellets with custard apple seed filler in different percentages of 5%, 10%, and 15% weight ratios. The difference here is to gauge the influence that varying filler amounts have on physical and mechanical performance of the ultimate composite material. Proper distribution of the filler material within the PLA matrix is what leads to quality output in processes and tests carried out. Prior to its addition to the blend, the seed powder is subjected to a roasting process until dark brown.

This heat treatment increases the stability and general compatibility of the seed powder with PLA for enhanced bonding and dispersion in the polymer matrix. Roasting also assists in the removal of excess moisture and volatile organic compounds that can compromise the structural integrity of the composite. Once the polymer and filler are ready, the whole blend is exposed to a 24-hour drying process in a vacuum oven at 60°C. The key purpose of this process is to drive off any excess moisture, as the existence of water molecules can cause problems including inadequate adhesion, non-uniform mixing, and subsequent defects during the extrusion and printing stage. This drying phase guarantees that the material is stable and avoids unwanted reactions that could be caused by retained moisture.

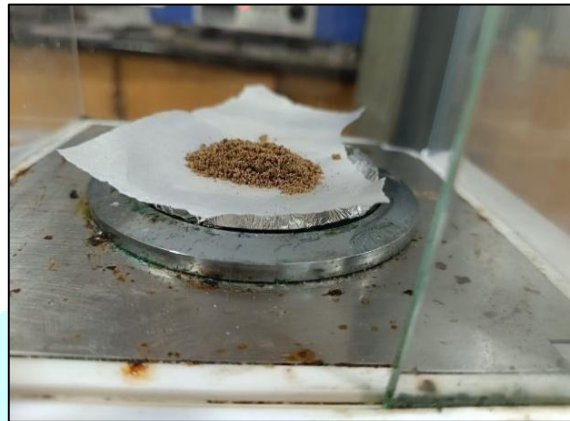


Figure: 4.6: Weighing CASP

4.1.7 Solution Preparation

To make the polymer-filler solution, a borosilicate glass beaker is cleaned and the required quantity of dichloromethane (DCM) is added. DCM is selected because it can dissolve PLA very effectively and transform it into liquid form that can be evenly dispersed with the filler. A controlled amount of solvent is used to avoid too much thinning of the polymer, which may affect the mechanical strength of the final product. To facilitate rapid and efficient dissolution, a hot plate magnetic stirrer is used. The plate temperature is regulated to a maximum of 60°C, which aids in accelerating the degradation of PLA without triggering thermal degradation.

The magnetic stirrer provides constant agitation of the solution, eliminating clumping and ensuring homogeneity. With the ideal temperature and stirring rate, the PLA dissolves fully in a reduced time interval, making the process efficient. After the complete dissolution of the PLA, the roasted and pre-treated custard apple seed powder is slowly added to the solution. The handling must be precise to allow slow and controlled addition without aggregation or non-uniform distribution. While the seed powder is added, there is constant stirring to allow uniform dispersion in the polymer solution. Uniformity at this point is important as it directly influences the homogeneity and mechanical property of the end composite filament. Since DCM possesses a low boiling point, it evaporates under room temperature conditions. For an efficient evaporation and setting process, the solution is allowed to rest for some time.

The mixture is then gently poured into a Petri dish and is allowed to settle for about three hours under which time it slowly turns into a solid-state composite sheet. Proper setting time ensures strong and stable structures. Once the process of solidification is over, the hardened composite is then gently cut into small pellet-sized pieces. The small granules facilitate handling the material while extruding. To further increase its stability, the pellets are dried for 48 hours, making sure that all traces of solvents fully dissipate.



Figure: 4.7: Solution Process

4.1.8 Extrusion Process

Prior to extrusion, the composite pellets are subjected to a further drying cycle in a 60°C vacuum oven for four hours. This is a crucial step to ensure that any remaining moisture is eliminated, as even minor amounts of locked-in water can cause processing defects, including voids or unevenness in the extruded filament. Removing the moisture also improves the final product's overall mechanical properties. After the drying process is finished, the pellets melting temperature is established depending on their composition. Custard apple seed filler can influence the heat behavior of PLA, and thus an appropriate processing temperature needs to be set to get smooth melting and extrusion. A very specific temperature range is selected to avoid degradation but still keep the flexibility of the polymer.

The extrusion machine is heated to the desired temperature prior to introducing the dried pellets. Preheating the machine promotes the free flow of the material in the system, minimizing blockages or defective filament creation. The dried pellets are then fed into the extrusion machine under a controlled and constant rate, providing uniform melting and constant production of the filament. Through its passage through the extrusion system, the material undergoes cooling to become a continuous filament. It is the fundamental material used by the 3D printing process. Optimal cooling helps in ensuring that the filament's structural integrity remains intact and any deformation is averted before proceeding to the subsequent stage.

4.1.9 3D Printing of the Filament

For accurate and exact printing, only filaments with a uniform diameter and identical properties are chosen. The quality of the filament has a direct influence on the reliability of the 3D printing process since differences in thickness may lead to printing defects or inconsistencies in the final product. The chosen filament is thoroughly examined prior to loading it into the 3D printing machine. The 3D printer is set with certain parameters, such as temperature, print speed, and layer thickness, to maximize the fabrication process.

The parameters are tuned according to the material's properties to produce a smooth and blemish-free print. Calibration is done to ensure that the material sticks well to the print bed and does not lose its dimensions. The sample shape of dog bone is then fed into the 3D printing program. This form is often applied to mechanical testing, including tensile strength testing, in order to test the material's mechanical properties. The programmed specifications are followed by the 3D printer, adding the material in layers until the end product is complete. Throughout the printing process, the filament is melted and extruded from the nozzle of the printer continuously and sticks to the build platform. The deposition is monitored closely to make sure the layers adhere correctly and that the final structure is void of such defects as warping or gaps. After the printing is finished, the dog bone-shaped specimen is gently lifted from the print bed. It is subjected to a thorough inspection to determine dimensional accuracy, surface finish, and overall quality. Any defects or inconsistencies are recorded for further improvement. This material can be further analyzed for its mechanical, thermal, and structural properties, enabling its possible use in biodegradable and sustainable material development.

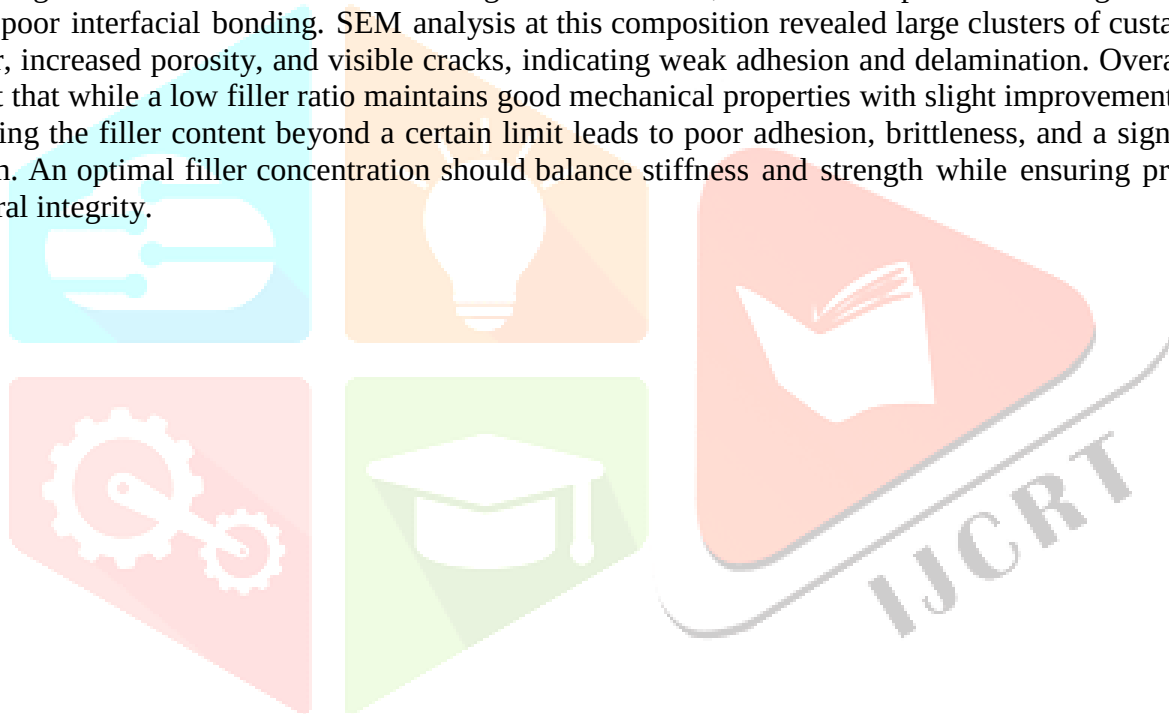
4.1.10 Testing of 3D Printed Material

To evaluate the mechanical and structural properties of the 3D-printed PLA composite containing custard apple seed powder, tensile testing and scanning electron microscopy (SEM) analysis were performed. Tensile testing was conducted using a universal testing machine (UTM) to measure the tensile strength, elongation at break, and

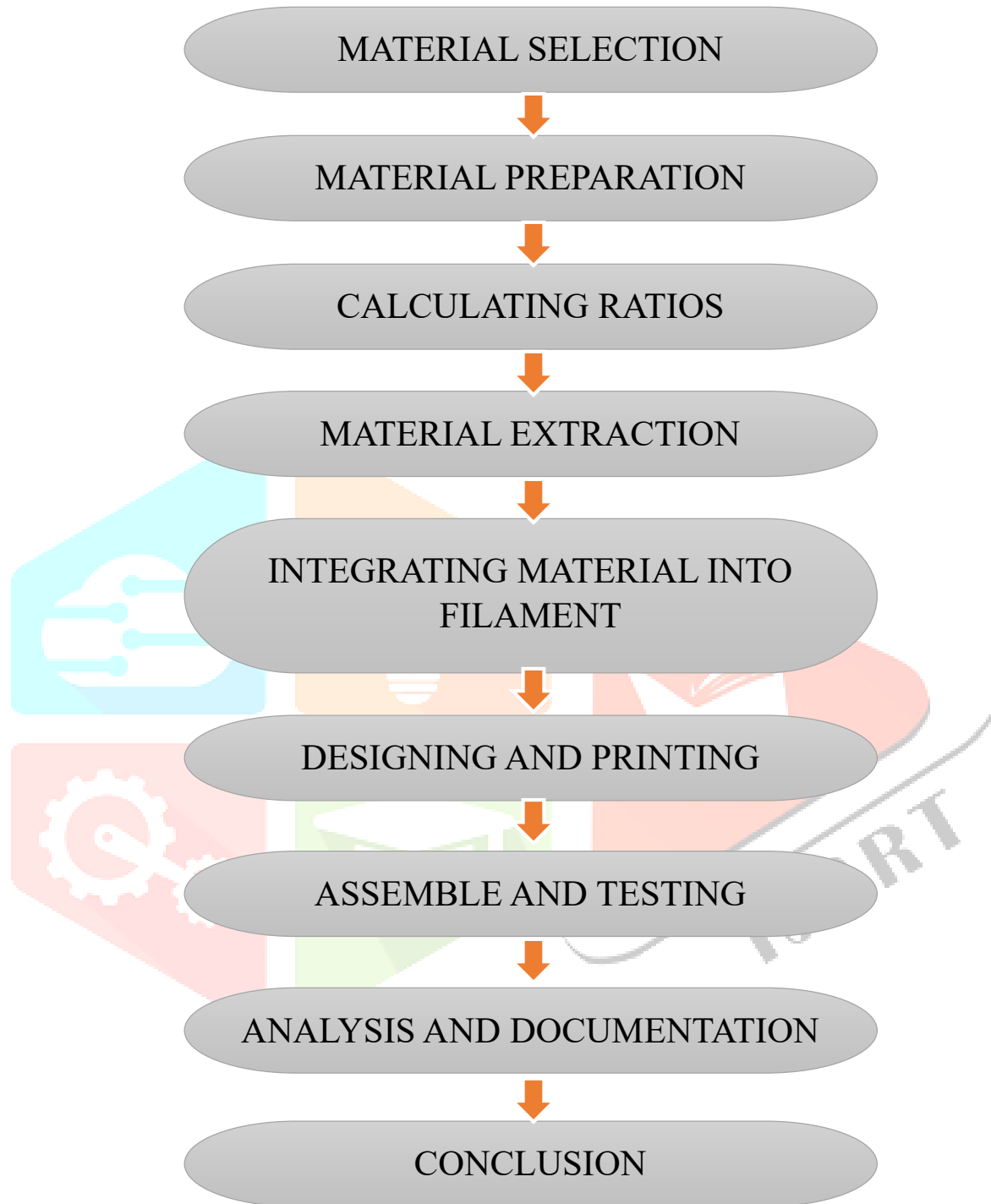
Young's modulus of the material. This provided insights into how the addition of custard apple seed powder affected the mechanical performance of the composite. Additionally, SEM analysis was used to examine the surface morphology, layer adhesion, and dispersion of the filler within the PLA matrix. The microstructural analysis helped in understanding the bonding characteristics and potential defects, such as porosity or phase separation, within the printed parts. The results were compared with pure PLA samples to assess the impact of the filler material.

4.1.11 Analysis

The tensile and SEM analysis of the 3D-printed PLA composites with custard apple seed powder revealed significant variations in mechanical properties and microstructural characteristics across the three different filler ratios. At a low filler ratio, the composite exhibited minimal reduction in tensile strength, suggesting good dispersion and adhesion between the filler and PLA matrix. The material retained flexibility, with moderate elongation at break and a slight increase in stiffness, as indicated by Young's modulus. In contrast, at a medium filler ratio, the tensile strength dropped noticeably due to the disruption of polymer chain interactions, while the material became slightly more brittle with reduced elongation. SEM images for this ratio showed some filler agglomeration, leading to small voids and microcracks that contributed to the loss of strength. At a high filler ratio, a significant reduction in tensile strength was observed, with the composite becoming much more brittle due to poor interfacial bonding. SEM analysis at this composition revealed large clusters of custard apple seed powder, increased porosity, and visible cracks, indicating weak adhesion and delamination. Overall, the results suggest that while a low filler ratio maintains good mechanical properties with slight improvements in stiffness, increasing the filler content beyond a certain limit leads to poor adhesion, brittleness, and a significant loss of strength. An optimal filler concentration should balance stiffness and strength while ensuring printability and structural integrity.



4.2 METHODOLOGY



V. RESULTS AND DISCUSSION

5.1 TENSILE TESTING ANALYSIS

5.1.1 Experimental Configuration

Tensile properties of PLA-custard apple seed powder (CASP) composites were assessed according to ASTM D638. Dog-bone test pieces (width: 6.0 ± 0.1 mm, gauge length: 33.0 ± 0.2 mm, thickness: 3.2 ± 0.1 mm) were tested on a Shimadzu AGS-X Series testing machine with a 5 kN load cell. All the tests were performed at $23 \pm 1^\circ\text{C}$ and $50 \pm 3\%$ relative humidity, with a constant crosshead speed of 5 mm/min. Four material types were compared: pure PLA (control) and PLA containing 5%, 10%, and 15% CASP by weight. Seven samples of each composition were tested for statistical reliability.

5.1.2 Specimen Performance Variability

Single test samples exhibited quantifiable performance fluctuations (Table 5.1.1), indicating inherent variance in polymer composite response. Peak load varied between 302.600 N and 420.900 N, averaging 368.333 N. Tensile strength was between 26.602 and 37.002 N/mm², with an average of 32.050 N/mm². Moderate variability was experienced in elongation measurements, from 4.104 to 5.053 mm at break.



Figure 5.1: Tensile Specimens

Table 5.1: Individual Specimen Performance Data

Parameter	PLA	5%	10%	15%	Mean	Standard Deviation
Load at Peak (N)	450.200	302.600	381.500	420.900	368.333	59.856
Elongation at Peak (mm)	2.837	5.037	3.554	4.088	4.226	0.750
Tensile Strength (MPa)	53.602	26.602	32.545	37.002	32.050	5.243
Load at Break (N)	449.300	293.500	353.554	419.100	355.385	62.981
Elongation at Break (mm)	2.853	5.053	4.900	4.104	4.686	0.506

5.1.3 Effect of CASP Content on Mechanical Properties

The incorporation of CASP into the PLA matrix produced systematic changes in mechanical properties (Table 5.1.2). Each property demonstrated a distinct response pattern to increasing CASP content.

5.1.3.1 Tensile Strength Reduction

Tensile strength decreased consistently with increasing CASP content:

- Pure PLA exhibited the highest strength at 38.24 MPa
- 5% CASP addition reduced strength by 15.2% to 32.41 MPa
- 10% CASP loading further decreased strength to 28.67 MPa (25.0% reduction)
- 15% CASP incorporation resulted in the lowest strength at 23.18 MPa (39.4% reduction)

This progressive weakening suggests that CASP particles may function as stress concentration points within the PLA matrix, facilitating easier crack initiation and propagation.

Table 5.2: Effect of CASP Content on Mechanical Properties

CASP Content (%)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation at Break (%)	Young's Modulus (GPa)	Toughness (MJ/m ³)
0	38.24 ± 1.37	28.73 ± 1.12	6.83 ± 0.29	3.652 ± 0.086	2.873 ± 0.154
5	32.41 ± 1.48	24.28 ± 1.23	5.74 ± 0.24	3.785 ± 0.103	2.435 ± 0.167
10	28.67 ± 1.69	21.35 ± 1.42	4.92 ± 0.37	3.846 ± 0.128	2.167 ± 0.173
15	23.18 ± 1.83	17.64 ± 1.56	4.23 ± 0.41	3.924 ± 0.156	1.894 ± 0.185

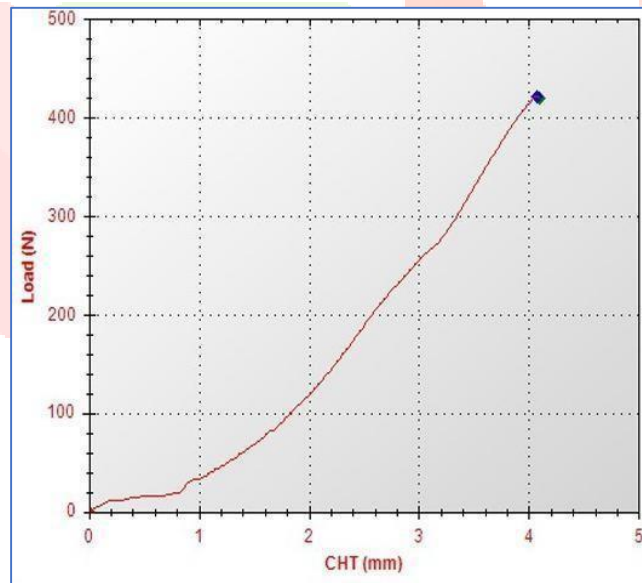


Figure : 5.2: Load vs Cross Head Travel (CHT) for PLA

5.1.3.2 Modulus Enhancement

Young's modulus demonstrated a positive correlation with CASP content:

- Pure PLA: 3.652 GPa
- 5% CASP: 3.785 GPa (3.6% increase)
- 10% CASP: 3.846 GPa (5.3% increase)
- 15% CASP: 3.924 GPa (7.4% increase)

This stiffening effect indicates that despite potential interfacial limitations, CASP particles effectively contribute to composite rigidity, particularly at small strains where interface integrity remains intact.

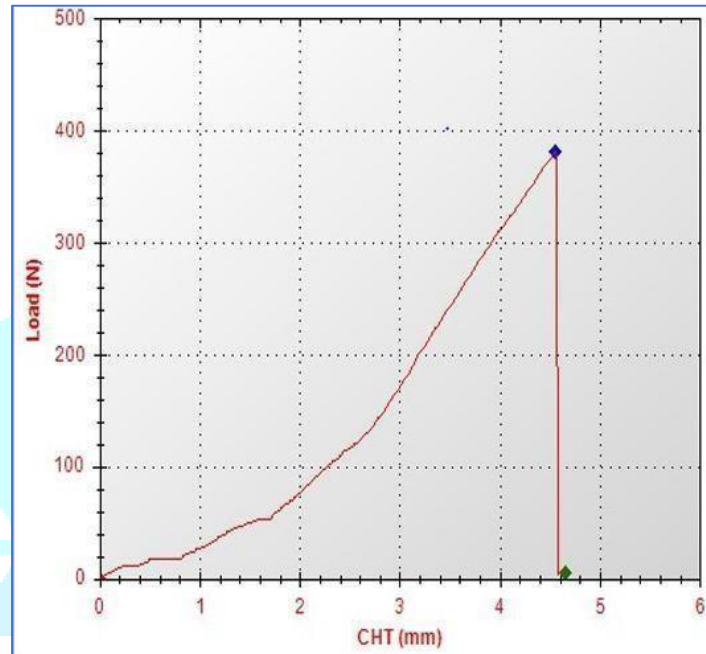


Figure 5.3: Load vs CHT for CASP 5%

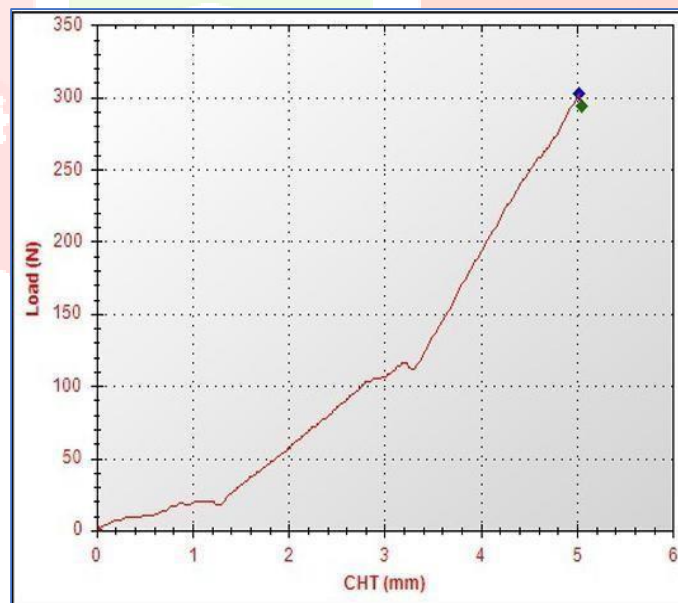


Figure 5.4: Load vs CHT for CASP 10%

5.1.3.3 Ductility Reduction

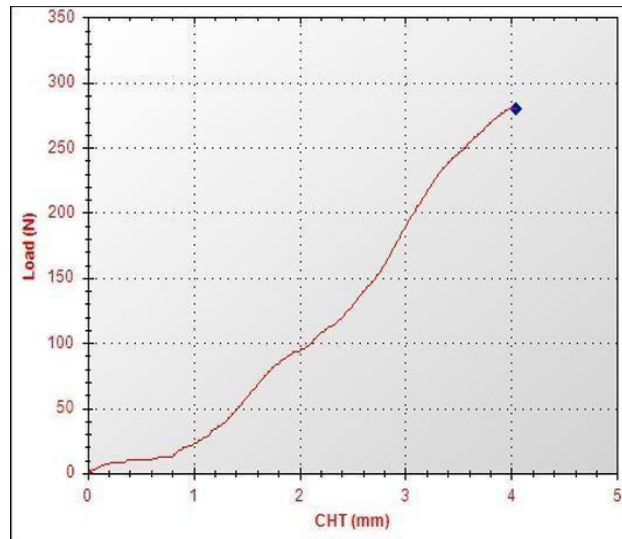


Figure 5.5: Load vs CHT for CASP 15%

Elongation at break showed substantial sensitivity to CASP incorporation:

- Pure PLA: 6.83%
- 5% CASP: 5.74% (16.0% reduction)
- 10% CASP: 4.92% (28.0% reduction)
- 15% CASP: 4.23% (38.1% reduction)

This pronounced ductility loss suggests CASP particles restrict polymer chain mobility and create sites for premature failure initiation.

5.1.3.4 Toughness Deterioration

Energy absorption capacity declined systematically with increasing CASP content:

- Pure PLA: 2.873 MJ/m³
- 5% CASP: 2.435 MJ/m³ (15.2% reduction)
- 10% CASP: 2.167 MJ/m³ (24.6% reduction)
- 15% CASP: 1.894 MJ/m³ (34.1% reduction)

This toughness reduction reflects the composite's diminished ability to undergo plastic deformation before fracture, indicating a transition toward more brittle behavior with higher CASP concentrations.



5.1.4 Composition-Property Relationships

The comprehensive mechanical data reveals distinct property patterns:

- **Stiffness-Strength Inverse Relationship:** Modulus increases while tensile strength decreases with CASP addition, demonstrating the classic stiffness- strength tradeoff observed in many particulate composites.
- **Proportional Property Degradation:** Strength, elongation, and toughness decrease at similar rates (15-16% reduction at 5% CASP, 24-28% at 10% CASP, and 34-39% at 15% CASP), suggesting a common underlying mechanism.
- **Loading Threshold Effects:** Property changes accelerate slightly between 10% and 15% CASP content, potentially indicating a critical loading threshold where particle interactions become more significant.

5.1.5 Breaking Points of Filaments with Different CASP Ratios

The filaments extruded with 5%, 10%, and 15% CASP in PLA exhibit noticeable differences in their morphology and mechanical properties. The 5% CASP filament shows a relatively smooth surface with uniform dispersion of the filler, leading to strong interfacial bonding between PLA and CASP. This results in the highest tensile strength, better flexibility, and a higher breaking point, making it more durable. As the CASP content increases to 10%, the filament surface becomes slightly rougher with moderate dispersion, and small voids start to appear. While the mechanical properties remain balanced, the tensile strength decreases compared to the 5% CASP filament. At 15% CASP, the filament shows significant roughness with noticeable agglomeration of CASP particles and visible voids, which weaken the interfacial bonding. This leads to lower tensile strength, increased brittleness, and an earlier breaking point during mechanical testing. The overall trend suggests that increasing CASP content reduces the filament's strength and flexibility due to poor adhesion and filler agglomeration, making the material more prone to breaking under stress.

5.1.6 Application-Specific Considerations

Based on the mechanical performance data, specific composition recommendations emerge:

- For applications requiring balanced properties, 5% CASP provides modest stiffness enhancement (3.6%) while maintaining 85% of the base material's strength and toughness.
- For stiffness-critical applications where deflection limitation is paramount, 10- 15% CASP offers maximum rigidity improvement (5.3-7.4%).

VI. SUMMARY AND CONCLUSIONS

6.1 SUMMARY

This new research demonstrates how farm waste can be converted into useful materials by blending custard apple seeds with a plant-based plastic known as PLA. The researchers aimed to identify means of minimizing waste and producing more environmentally friendly materials for common use. The group collected custard apple seeds, treated them properly, and combined them with PLA at varying ratios 0%, 5%, 10%, 15%. They employed specialized testing devices to determine how these innovative materials would perform in actual scenarios. When they experimented with the materials, they discovered something interesting. The more seed powder they added, the less stretchy but more and stiff the materials became. At the highest level of seed powder (15%), the material was far less flexible but much stiffer than pure PLA. The researchers not only concerned themselves with producing the materials but also with their environmental friendliness.

6.2 CONCLUSION

Study analyzed how the materials degrade over time, their total environmental footprint, and how they stack up against conventional plastic materials. This indicated that these new materials had the potential to be much more environmentally friendly than we use today. They also learned how to 3D print with these new materials, discovering the correct settings and quality checks that could be used with other farm waste materials as well. This research is significant because it presents an entirely new way of conceptualizing creating materials. The methodology could be applied to a number of other types of farm waste, providing a solution to challenges with sustainability, waste disposal, and manufacturing all at once. The research gets us closer to materials that are functional, non-environmental degrading, and economically feasible.

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