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Original Article

Selection of Single and Multiple Fillers for Ease of FDM 3D Printing using Combined Approach of Property Improvement Function & Analytic Hierarchy Process (AHP)

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Abstract - *The high cost and complexity involved in producing composite filaments limit their use compared to typical polymer filaments. Unlike pure polymer filaments, composite filaments integrate reinforcing agents or fillers that can disrupt the uniformity of the polymer matrix. The poor dispersion of fillers leads to agglomeration, hindering the printing process and reducing key properties such as mechanical strength and thermal or electrical conductivity. The inclusion of fillers complicates not only filament manufacturing and 3D printing but also influences the overall performance of the printed parts. The challenge intensifies when multiple fillers are used. This impact can collectively be termed as affecting the "ease of 3D printing." Selecting suitable fillers is critical, as they influence filament quality, printing behavior, and final product performance. This study adopts the Performance Improvement Function (PIF) and Analytic Hierarchy Process (AHP) as a tool for selecting both single and multiple fillers, keeping the goal as improvement of Mechanical, Thermal, and Rheological properties and ease of FDM 3D printing. The fillers were initially graded based on the increments or decrements they show in Mechanical, Thermal and Rheological properties using PIF. The top 4 fillers were then chosen as alternatives and were ranked using AHP.*

Keywords - *Additive Manufacturing (AM), FDM 3D Printing, Ease of 3D Printing, Composite Filament, AHP.*

1. Introduction

In FDM 3D printing, the use of composite filaments has been found to improve various properties such as tensile strength, flexural strength, elongation, electrical conductivity, etc. [1-3] of end products. It was found that by adding glass in three different micro/nano forms as reinforcement in PLA, significant improvements have been observed in most of the mechanical properties of all types of glass particles employed. The mechanical properties considered in the study were impact strength, micro-hardness, tensile strength, and flexural properties [4]. In one of the studies, Cellulose Nano crystals and Carbon Nano Tubes were incorporated into the ABS matrix for FDM 3D printing. It was found that due to the addition of CNC and CNT, the tensile strength improved by 81%, the elastic modulus improved by 95%, while the interlaminar strength was improved by 102% [5]. In one of the works, Spray Dried Cellulose Nano Fibrils (SDCNF) were compounded into a polypropylene matrix as a reinforcing material. The results suggest that SDCNF particles with high aspect ratios and low circularity contribute to the enhancement of tensile and flexural properties [6]. There are some challenges in the use of fillers in making composite filaments. The most predominant are the dispersion of the fillers in the polymer matrix and the interfacial bonding between the fillers and the polymer matrix [7]. Although there are methods to ensure proper dispersion and enhance interfacial bonding, which include optimum process parameters, multiple time extrusion, surface modification, etc. [8] The use of a single filler normally addresses a single property at a time, such as mechanical strength or electrical conductivity. Mono-filler PLA composites with Graphene Nanoplatelets (GNPs) or Multi-Walled Carbon Nanotubes (MWCNTs) have shown significantly increased conductivity and thermal properties over neat PLA due to effective filler networks [9]. PLA reinforced with Cellulose Nano crystals (CNCs) exhibited up to 18 % increase in tensile strength compared to neat PLA when 1 wt. % CNCs were added, demonstrating improved mechanical performance with a single biodegradable filler [6].

In order to address more than one property at a time, researchers have tried to make use of more than one filler at a time [3, 10]. PLA composites containing both GNPs and MWCNTs showed synergistic improvements in electrical conductivity and mechanical stiffness relative to mono-filler systems because the dual fillers form more efficient interconnected networks [9]. PLA filled with hybrid rice husk flour and bio carbon achieved more than 100 % increases in tensile and flexural strengths, along with better thermal stability and moisture resistance, outperforming neat PLA and single-filler composites [11]. With the use of multiple fillers, the dynamics of the interrelation between the polymer matrix and the fillers change. This is because there are two different materials added to the matrix. Their extent of compatibility with the polymer matrix would be different. A comparative study between the use of fillers individually and complimentary to each other is required. The selection of such fillers which would complement each other when used together is to be investigated.

“Ease of 3D printing” is the ease with which a filament can be used for 3D printing to manufacture a good-quality end product. It is not limited to basic properties requirement by the application where the end product will be used. Additionally, it concerns the color, texture and shape of the product from an aesthetic and ergonomic point of view. [12]

There has been reported literature on the use of multi-criteria decision-making tools for material selection. A structured method to select natural fiber-reinforced polymer composites for automotive parts using the Analytic Hierarchy Process (AHP) with Expert Choice 11 software was proposed in a study [13]. A database of 29 composites was created, focusing on density, Young’s modulus, and tensile strength. AHP was then used to identify the best material for an automotive dashboard panel based on key mechanical and physical properties. Sensitivity analysis confirmed that a composite of 60% kenaf and Polypropylene (PP) was the most suitable choice. An AHP-based system was developed [14] to select the most suitable natural fiber for reinforcing biopolymer composites in food packaging. 13 relevant properties were evaluated, and 9 natural fibers were ranked using Expert Choice 11.5 software based on data from recent studies. A study was conducted to design a Natural Fiber-Reinforced Biopolymer Composite (NFBC) container [15] using a hybrid approach combining the Kano Model, Quality Function Deployment for Environment (QFDE), morphological chart, and AHP. Focusing on a biodegradable sugar palm fiber–sago starch composite, the study translated customer needs into technical criteria, generated design options, and selected the best Concept (CD18), a rectangular clamshell container with ribbing and locking features based on performance, size, and cost. The work highlights the use of concurrent engineering for sustainable packaging design. A method combining AHP and Vekriterijumsko KOmpromisno Rangiranje (VIKOR) was proposed [16] to select natural fibers for automotive side-door impact beam composites. The study evaluated and ranked various fibers, identifying kenaf as the best option with the lowest VIKOR score (Q = 0.0000). The authors concluded that this integrated approach offers a systematic and reliable material selection process for automotive applications. In a research, a multi-criteria material selection method using the Analytic Network Process (ANP) was used [17], highlighting its advantage over AHP by allowing feedback and interdependence between criteria and alternatives. A study was applied to select non-metallic gear materials for aircraft systems. The study considered thermal, mechanical, and weight factors. It showed that clustering criteria aid in weight assignment and sensitivity analysis, especially for complex or large-scale problems. The findings confirmed ANP's effectiveness in handling intricate material selection tasks with multiple performance requirements. When one wants to employ single filler (Natural or synthetic), what are the available choices and their rankings and what are the choices of fillers and rankings in case of multiple fillers is presented in this study. In view of this, it is very important to decide the correct fillers, which would enhance the properties of the polymer filament and ensure ease of 3D printing. MCDM techniques can be effectively used for selecting the fillers based on predefined parameters. The current work is about the use of Analytic Hierarchy Process (AHP) for taking decision on the selection of fillers.

1.1. Hybrid Filaments for FDM 3D Printing

It is evident from many studies that due to the addition of fillers in the polymer matrix of the filament for FDM 3D printing, properties of the material, such as tensile strength, flexural strength, electrical and thermal conductivity, etc., are improved. The incorporation of nano-SiO_2 as a synthetic filler in PLA for FFF improved mechanical properties at low loadings due to enhanced matrix–filler interactions, whereas higher filler content led to reduced mechanical performance but imparted mild antibacterial functionality [1]. Mg-filled PLA composite filaments incorporating vitamin E were successfully processed for additive manufacturing, where vitamin E enhanced Mg–PLA integration, enabling stable filament extrusion and defect-free 3D printing of implant components despite non-uniform filler dispersion, demonstrating the feasibility of this approach for biomedical applications [16].

The mechanical performance of FDM-printed PLA composites depends strongly on filler type and print orientation, with ceramic- and metal-filled PLA showing comparable or improved properties relative to neat PLA, while wood- and poorly bonded fiber-filled systems exhibited reduced strength, whereas short carbon fiber reinforcement significantly enhanced stiffness, strength, and interlayer integrity due to fiber alignment along the print direction [17]. A PA12 composite reinforced with ceramic bio fillers exhibited enhanced thermal stability and stiffness when processed via FDM, with a slight reduction in strength due to porosity, while maintaining printability and showing potential suitability for biomedical and bone-related applications [15].

ABS–MWCNT composite filaments for FDM exhibited improved tensile performance at moderate nanotube loadings due to effective dispersion, while higher loadings increased melt viscosity, promoted agglomeration, and reduced strength, indicating an optimal filler content that balances mechanical enhancement and printability, with hybrid filler systems further enabling multifunctional property improvements such as electrical conductivity [2]. PLA composites reinforced with cuprous oxide and cellulose Nano fibrils showed enhanced mechanical properties and strong antibacterial activity at low, optimized filler loadings due to synergistic interactions and uniform dispersion, demonstrating their suitability for high-performance FDM applications [3].

Multifunctional PA12 Nano composites reinforced with TiN and Cu/Cu_2O exhibited improved mechanical performance and antibacterial functionality for FDM 3D printing, enabled by effective filler dispersion achieved through thermo-mechanical processing [6]. PA12 Nano composites reinforced with TiN and Cu/Cu_2O demonstrated enhanced tensile performance and antibacterial activity, with Cu_2O showing superior antimicrobial effectiveness for medical-grade FDM applications, while silane-treated microcrystalline cellulose was shown to improve filler–matrix compatibility through surface modification [8].

The objective of this research paper is to review the various kinds of fillers, their effects on filament, process ability, properties of 3-D printed products, and grading based on the increments or decrements they show in Mechanical, Thermal and Rheological properties using PIF and rank them using AHP.

2. Research Methodology

There are some fillers which are very extensively used in literature, such as CNF, flax, Jute, wood flour, Graphene Nano fibers, etc. Such fillers were considered for the study. The selection of fillers for ease of 3D printing is done in two stages. In stage 1, using the PIF, fillers are shortlisted. In order to make a base for paired comparison, the response of an alternative to various parameters of 3D printing was studied, referring to the literature. In stage 2, using the AHP methodology selection of the best fillers for ease of 3D printing is done. The entire process for the selection of fillers using PIF and AHP is shown in Figure 1. This method of using PIF is unique since, in this case, shortlisting of fillers is done using the effect of that filler on properties of the 3D printed part, while in other studies, the properties of the fillers were considered as base line for further analysis.

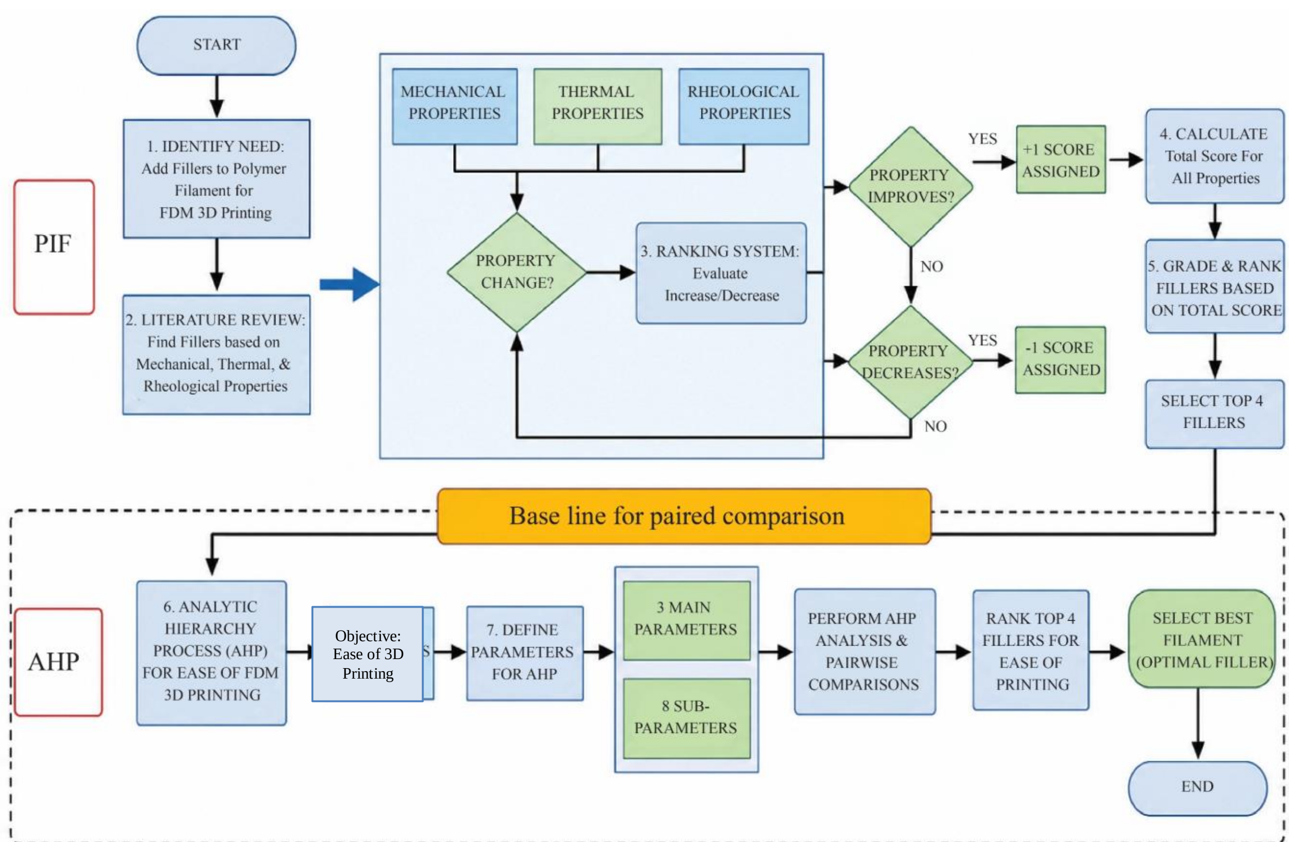

Fig. 1 Methodology for selection of fillers

The selection of fillers is first done using PIF. In this method, weights are assigned to various fillers based on their contribution in enhancement or reduction of Mechanical, Thermal and Rheological properties. Tensile strength, Young's Modulus, Ductility, and Flexural strength were considered under mechanical properties and designated as M1, M2, M3 and M4, respectively. Thermal conductivity and Glass Transition Temperature were considered under thermal properties. These are denoted as T1 and T2, respectively. Rheology behavior and Melt Flow Index are kept under the rheological properties head with notations R1 and R2, respectively. A score of +1 is assigned if the addition of a particular filler enhances a specific property. A score of -1 is associated with a decrease in the property, while 0 is for no change in the property with the addition of fillers. PIF was then estimated as per equation (1).

PIF = f (Tensile Strength, Young's Modulus, Ductility, Flexural Stress, Thermal Conductivity, Glass Transition Temperature, Rheology, Melt Flow Index)

$$(PIF)_i = \sum_1^n (f_{M1i}, f_{M2i}, f_{M3i}, f_{M4i}, f_{T1i}, f_{T2i}, f_{R1i}, f_{R2i}) \quad (1)$$

$$Accepted\ for\ further\ analysis = (PIF)_i > 0$$

The fillers with positive PIF values were then considered for further analysis.

After this step, the top 4 fillers with the highest value of PIF were then considered for further analysis.

2.1. Formation of Baseline for Paired Comparison

In AHP, paired comparison is the most important aspect. Many researchers have used many methods for making the paired comparisons. [13, 14, 18]. In many studies, material properties are considered the baseline for paired comparison. In our case, where our objective is ease of 3D printing, considering the material properties would not be a suitable option, so we have made the baseline for the paired comparison. This base line is based on the response of an alternative to various parameters/sub-criteria of 3D printing. Every alternative is rated as per its response towards the sub-criteria for ease of 3D printing based on the predefined scale shown in Table 1.

Table 1. Rating given to various sub-criteria

Rating	Description
5	Not affecting printing
4	Slightly affecting printing
3	Affecting printing
2	Difficult to print
1	Very difficult to print
0	Not printable

The response of every alternative to a sub-criterion for ease of 3D printing would be different. Table 2 shows a sample response of alternatives (A1 to A4) on a scale of 5 to sub criteria of 3D printing (C1 to C4). The ratings are as per the predefined rubric, as shown in Table 1.

Table 2. Response of an alternative to a sub-criterion

Alternatives	3D printing sub-criteria			
	C1	C2	C3	C4
A1	3	5	2	1
A2	4	2	4	3
A3	5	3	2	3
A4	4	2	1	5

As an example, if CNC/CNF is used as filler and it does not lead to void formation, then a rating of 5 would be assigned to it. If the use of Bamboo as filler leads to void formation, then a rating of 2 would be assigned. All the alternatives would be rated on a scale of 5 for various sub-criteria depending on their effect on the 3D printing process. These values would then be used for the purpose of paired comparison so that the comparisons would be consistent. The AHP framework would be used for getting the best filler for ease of 3D printing.

2.2. Analytic Hierarchy Process

AHP is a multi-criteria decision-making technique. The first step in AHP is to structure the decision problem into a hierarchical framework consisting of the goal, criteria, and alternatives**.** In the next step, a pairwise comparison matrix is constructed in which each criterion is compared with every other criterion based on their relative importance using some predefined scale. The pairwise comparison matrix is represented as

$$A = [a_{ij}]$$

Where $a_{ij} = \frac{Importance\ of\ criterion\ i}{Importance\ of\ criterion\ j}$

Thus, the matrix takes the form.

$$\begin{bmatrix} 1 & a_{12} & a_{13} & \dots & a_{1n} \\ 1/a_{12} & 1 & a_{23} & \cdots & a_{2n} \\ 1/a_{13} & 1/a_{23} & 1 & \cdots & a_{3n} \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & 1/a_{3n} & \cdots & 1 \end{bmatrix} \quad (2)$$

where the elements satisfy the condition

$$a_{ii} = 1$$

$$a_{ij} = \frac{1}{a_{ji}}$$

Subsequently, the pairwise comparison matrix is normalized by first computing the column sums.

$$S_j = \sum_{i=1}^{n} a_{ij}$$

The normalized matrix elements are then obtained as:

$$N_{ij} = \frac{a_{ij}}{s_j} \quad (3)$$

Where N= $[N_{ij}]$ represents the normalized matrix, the priority weight vector corresponding to the relative importance of the criteria is calculated by averaging the rows of the normalized matrix as follows:

$$w_i = \frac{1}{n}\sum_{j=1}^{n} N_{ij}$$

Which yields the weight vector $$W = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \vdots \\ w_n \end{bmatrix}$$

Subject to the condition

$$\sum_{i=1}^{n} w_i = 1$$

To ensure the reliability of the judgments, a consistency test is performed. First, the weighted sum vector is obtained as:

AW=A×W

The consistency vector is then calculated using:

$$\lambda_i = \frac{(AW)_i}{w_i}$$

The maximum eigenvalue of the matrix is determined as:

$$\lambda_{max} = \frac{\sum_{i=1}^{n} \lambda_i}{n}$$

Using this value, the consistency index (CI) is computed as:

$$CI = \frac{\lambda_{max} - n}{n-1}$$

where n represents the number of criteria, the Consistency Ratio (CR) is then calculated using:

$$CR = \frac{CI}{RI}$$

where R is the random index obtained from Saaty's standard table. The decision matrix is considered consistent when

CR<0.1

Otherwise, the pairwise comparisons must be revised.

Following the determination of criteria weights, pairwise comparison matrices are similarly constructed for the alternatives with respect to each criterion.

For criterion C_k, the comparison matrix is denoted as:

$$A^{(k)} = [A_{ij}{}^{(k)}]$$

from which the local priority vector is obtained as:

$$W^{(k)} = \begin{bmatrix} w_1{}^{(k)} \\ w_2{}^{(k)} \\ \vdots \\ w_n{}^{(k)} \end{bmatrix} \quad (4)$$

Finally, the global priority score of each alternative is calculated by combining the criteria weights with the local priorities using:

$$P_i = \sum_{k=1}^{n} w_k w_i{}^{(k)}$$

where w_k denotes the weight of criterion k, the alternative with the highest priority value represents the most suitable material for the intended application. In matrix form, the final ranking can also be expressed as:

$$P = W_c X\, W_A \quad (5)$$

The alternatives will be ranked based on this final score of various criteria and sub-criteria.

where W_C represents the criteria weight vector, and W_A denotes the matrix of alternative weights with respect to each criterion. The alternative corresponding to the maximum value of Pi is selected as the optimal material.

AHP was used in the current work for selecting single fillers and multiple fillers for the goal of ease of 3D printing. Figure 2 depicts the entire process of AHP.

AHP is a tool for decision-making with multiple criteria and multiple alternatives, as shown in Figure 2. It is based on paired comparisons for the importance of various criteria and alternatives over others. In the current work, 8 different sub-criteria have been considered, which are categorized under three different criteria, namely filament manufacturing, 3D printing process and 3D printed part as listed in Table 3. For the purpose of pairwise comparison, domain experts were consulted.

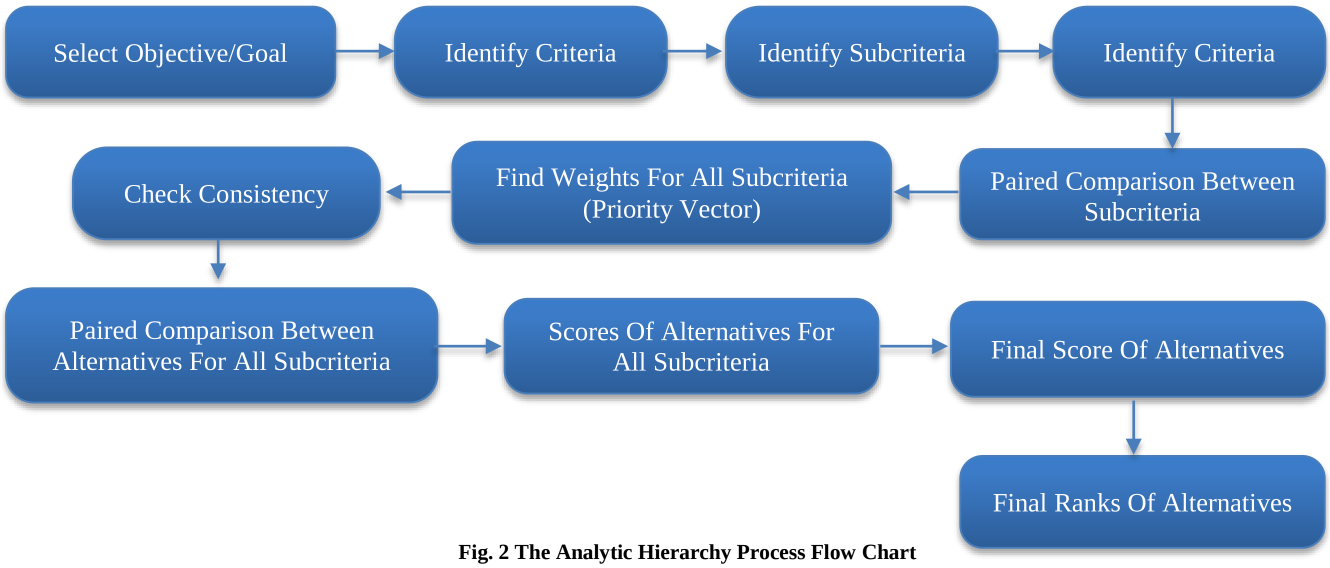

Fig. 2 The Analytic Hierarchy Process Flow Chart

Table 3. Parameters for ease of 3D printing

Main parameter/Cluster	Sub parameter	Description
Filament manufacturing	Voids %	To ensure proper bonding during 3D printing
	Diameter uniformity	To ensure the smooth passage of the filament through the nozzle.
	Dispersion of fillers	Improper mixing results in non-uniform printing
	Rheological properties	To ensure uniform printing.
3D printing	Nozzle clogging	To ensure smooth printing
	Interlayer bonding	To ensure that the part is strong.
3D printed part	Part Color	Proper aesthetic appearance
	Part surface texture	Proper aesthetic appearance

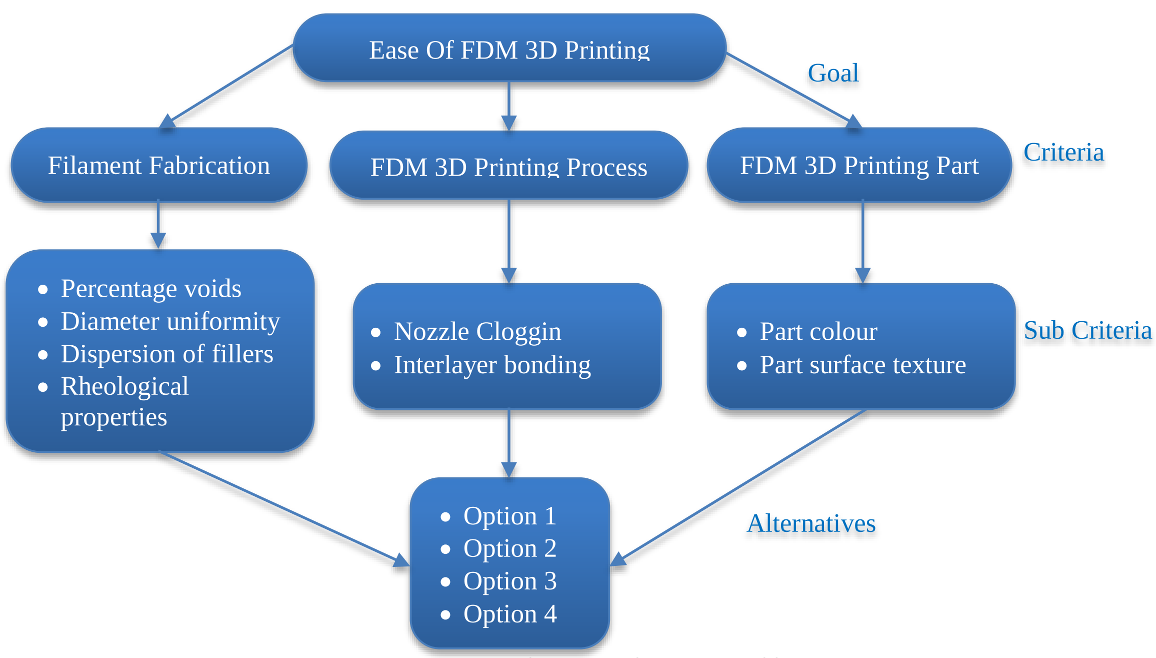

Fig. 3 The AHP framework for selection of fillers

Referring to the literature, the ease of 3D printing for various alternatives under each sub-criterion was estimated considering the behavior at optimum loading of the fillers. The effect of a few sub-criteria on the ease of 3D printing was not found in the referred literature. For such sub-criteria, the ratings of some other sub-criteria in that Cluster were considered and assigned. For example, if the rating for an alternative for "percentage of voids" from the cluster "filament manufacturing" is 3, and the rating for "dispersion of fillers" was not found from the referred literature, then it was taken as 3, as both belong to the "filament manufacturing" Cluster. The same approach was adopted for all such properties that were not found in the literature. Figure 3 shows the Goal, Criteria, Sub-criteria and Alternatives for the current study. Initially, the weightages of all 8 sub-criteria were estimated using paired comparison through domain experts and the results are shown in Table 10.

3. Data Analysis

3.1. Performance Improvement Function (PIF)

The results of PIF for Natural fillers, Synthetic Fillers and Multiple fillers are as listed in Tables 4, 5 and 6, respectively. Table 4 shows that Hemp, Harakeke, Jute, Flax, Basalt, CNC, Bamboo, Pine wood and Kenaf fibers show positive PIF as they mostly present a favorable impact on filament and printed products. The rest of the present adverse effects cannot be considered for further analysis.

Table 4. Natural fillers used in composite filament

Filler	Mechanical				Thermal		Rheological			Reference
	M1	**M2**	**M3**	**M4**	**T1**	**T2**	**R1**	**R2**	**PIF**	
Wood	-1	-1	-1	-1	+1	+1	+1	-1	-2	[15, 16, 19]
Oil Palm Fiber	-1	+1	-1	-1	+1	+1	-1	-1	-2	[17, 20-22]
Birch Fiber	-1	+1	-1	+1	+1	+1	-1	-1	0	[5, 7, 15]
Hemp	+1	+1	+1	+1	-1	+1	-1	-1	2	[23]
Harakeke	+1	-1	+1	+1	+1	+1	-1	-1	2	[23-26]
Jute	+1	+1	-1	+1	+1	+1	-1	-1	2	[27, 28]
Rice straw	-1	+1	-1	+1	+1	+1	-1	-1	0	[29]
Flax	+1	+1	-1	+1	+1	+1	-1	-1	2	[27, 30]
Sugarcane bagasse	+1	+1	-1	-1	-1	0	-1	-1	-3	[31, 32]
Lignin	-1	+1	-1	+1	+1	0	-1	-1	-1	[33-35]
Basalt	+1	+1	+1	+1	-1	+1	-1	-1	2	[29]
Macademia nut shell	0	+1	-1	+1	0	0	-1	-1	-1	[29, 36]
CNC	+1	+1	-1	+1	+1	0	-1	+1	3	[37, 38]
Coir	0	+1	-1	+1	0	0	-1	-1	-1	[29, 39]
Bamboo	+1	+1	-1	+1	+1	0	-1	-1	1	[29]
Pine Wood	+1	+1	+1	+1	0	0	-1	-1	2	[29]
Kenaf	+1	+1	-1	+1	+1	0	-1	-1	1	[40]

M1 – Tensile Strength, M2 –Young's Modulus M3- Ductility M4- Flexural Stress. T1- Thermal Conductivity, T2 – Glass Transition Temperature (T_g) R1- Rheology R2 – Melt Flow Index

PIF evaluation of Synthetic fillers is presented in Table 5. Al_2O_3, ZrB_2, Cu, Al, Long C Microfiber, Graphene, short glass fiber and MWCNT are found to be promising synthetic fillers as they show positive PIF. Bronze has a larger negative PIF, which indicates restrictions on its use in polymer composites.

Table 5. Synthetic fillers used in composite filament

Filler	Mechanical				Thermal		Rheological			Reference
	M1	**M2**	**M3**	**M4**	**T1**	**T2**	**R1**	**R2**	**PIF**	
Al_2O_3	0	+1	-1	+1	+1	0	-1	-1	1	[41-43]
TiO_2	-1	+1	-1	+1	+1	+1	-1	-1	0	[41, 44, 45]
ZnYO	-1	0	1	0	0	0	0	0	0	[41]
$BaTiO_3$	0	+1	-1	+1	+1	0	-1	-1	0	[41]
ZrB_2	+1	+1	-1	+1	+1	0	-1	-1	1	[41]
Fe	0	+1	-1	+1	+1	0	-1	-1	-2	[41, 46]

Cu	0	+1	-1	+1	+1	+1	0	-1	2	[41, 47, 48]
W	-1	+1	-1	+1	0	0	-1	-1	-1	[41]
Bronze	-1	-1	-1	-1	+1	0	-1	-1	-5	[41, 49, 50]
Al	+1	+1	-1	-1	+1	0	-1	+1	2	[41, 51, 52]
Long C Microfiber	+1	+1	-1	+1	+1	0	-1	-1	1	[41, 53, 54]
Mm scale C fiber	0	-1	0	-1	1	1	-1	-1	-1	[41, 53, 54]
Graphene	+1	+1	-1	+1	+1	+1	-1	-1	2	[9, 16, 41, 55]
MWCNT	+1	+1	-1	+1	+1	+1	-1	-1	2	[9, 16]
Short glass fiber	+1	+1	-1	+1	+1	0	-1	-1	1	[41, 56, 57]
Zeolite	-1	+1	+1	+1	+1	0	-1	-1	3	[41, 58, 59]
Montmorillonite	+1	+1	-1	+1	+1	0	-1	-1	1	[41, 60, 61]

Table 6 raises the PIF evaluation of multiple fillers, which is the inclusion of more than one filler in the polymer filament. In such cases, Flax+ Glass veil + Biorez and CNF+CuO combinations of fillers showed favorable effects as indicated by high PIF. The combination of Jute and NaCl presented a large negative PIF, which indicates restrictions on the combination; however, Jute performs better when it is a single filler.

Table 6. Multiple fillers used in composite filament

Filler	Mechanical				Thermal		Rheological			Reference
	M1	M2	M3	M4	T1	T2	R1	R2	PIF	
Al/Al_2O_3	-1	+1	-1	+1	+1	0	-1	-1	0	[62-65]
SiC/Al_2O_3	+1	+1	-1	+1	+1	0	-1	-1	1	[41, 65]
Colophony/Wood Flour	+1	-1	-1	0	+1	0	-1	0	-1	[66]
Jute fiber/NaCl	-1	-1	-1	-1	+1	+1	-1	-1	-4	[67]
Carbon/Jute fiber	-1	-1	+1	+1	-1	-1	-1	-1	-2	
Jutefiber/NaCl/Mayan Yellow	-1	-1	+1	+1	-1	-1	-1	-1	-2	
Flax+Glass veil+Biorez	+1	0	+1	+1	+1	+1	-1	-1	3	[30]
Flax+Biorez	-1	+1	-1	+1	0	0	-1	-1	0	
Non-crimp Fabric Flax+Biorez	-1	+1	-1	+1	+1	-1	-1	-1	0	
Ni+Cu	+1	+1	-1	+1	+1	0	-1	-1	1	[68]
Lignin+Arboform	-1	+1	-1	+1	+1	0	-1	-1	-3	
Kenaf+CNF+Nanoclay	+1	+1	-1	+1	+1	-1	-1	-1	0	[69]
CNF+CuO	+1	+1	+1	+1	+1	0	-1	-1	3	[3]
CuO+TiN	+1	+1	-1	+1	+1	0	-1	-1	1	[10]

After careful observation of the PIF evaluation, fillers with positive PIF are considered for further ratings based on filament fabrication, 3D-printing and appearance of the printed part. Tables 7, 8 and 9 show these ratings for natural fillers, synthetic fillers and multiple fillers, respectively. Table 7 shows the ratings given to the alternatives for ease of 3D printing.

The rubric used for this rating is shown in Table 1, which varies between 5 (Not affecting printing) and 1 (not printable). Every alternative is rated for every sub-parameter depending on the effect of that sub-parameter on 3D printing. A rating of 5 is given to CNC/CNF for dispersion of fillers indicting that when CNC/CNF is added in polymer, these fillers get uniformly dispersed in the matrix and do not affect printing. Table 7 forms the basis for a paired comparison between the various alternatives for natural fillers.

The relative importance of one filler over the other for a specific sub-parameter can be established from this table. As an example, the score for sub parameter “%Voids” for CNC/CNF is 5, while it is 3 for Harakeke. It means CNC/CNF has more weightage than Harakeke as far as void formation in the filament is concerned.

This is shown in Table 11 with a rating of 1.667 for CNC/CNF compared to Harakeke and 0.6 for Harakeke compared to CNC/CNF. Other alternatives for the other sub-parameters are also compared in the same way and are listed in table 11. The results of the normalized values of all the alternatives for natural fillers are shown in Figure 4.

Table 7. Ratings for various sub-criteria for natural fillers

	FILAMENT FABRICATION				3D PRINTING		3D PRINTED PART		
	Voids %	**Diameter uniformity**	**Dispersion of fillers**	**Rheological properties**	**Nozzle clogging**	**Interlayer bonding**	**Part Color**	**Part surface texture**	**Ref**
Harakeke	3	3	3	3	3	3	3	3	[23]
Hemp	3	3	3	3	3	3	3	3	[23]
Jute	3	4	4	4	3	3	3	3	[27, 67]
Flax	4	4	4	4	5	4	4	4	[30]
Basalt	4	4	4	4	4	4	4	4	[29]
CNC/CNF	5	5	5	5	5	5	2	2	[37] [38]
Bamboo	2	2	2	2	3	3	3	3	[29]
Pine Wood	3	3	3	3	3	3	2	2	[29]
Kenaf	4	4	4	4	4	4	3	3	[40]

Ratings for various alternatives of synthetic fillers using the rubric of table 1 are listed in table 8. Table 8 forms the basis for a paired comparison between various alternatives for synthetic fillers. As an example for the "% Voids" sub-parameter, from Table 8, the rating for graphene is 4, while for zeolite it is 3. It means graphene has more weightage than zeolite. On the basis of these ratings, a paired comparison between various alternatives is done. For the purpose of uniformity, these results are normalized and listed in Figure 5. Figure 5 shows that the normalized value for graphene compared to zeolite is 0.162, and zeolite compared to graphene is 0.036. The rating for all the alternatives of synthetic fillers is listed in Table 8. The results of the normalized values of all the alternatives for synthetic fillers are shown in Figure 5

Table 8. Ratings for various sub-criteria for synthetic fillers

	FILAMENT FABRICATION				3D PRINTING		3D PRINTED PART		
	Voids %	**Diameter uniformity**	**Dispersion of fillers**	**Rheological properties**	**Nozzle clogging**	**Interlayer bonding**	**Part Color**	**Part surface texture**	**Ref**
Montmorillonite	3	3	3	3	3	3	3	3	[60, 61]
Graphene	4	4	4	4	4	4	3	4	[70]
MWCNT	4	4	4	3	3	3	3	3	[2]
Long C Microfiber	3	3	3	3	3	3	3	4	[53]
ZrB2	3	3	3	3	3	3	3	3	[41]
Al2O3	3	4	4	3	4	4			[62, 63]
Cu	3	3	3	4	4	4	4	4	[47, 48]
Short G fiber	3	3	4	4	4	4	4	4	[56, 57]
Zeolite	3	3	3	3	3	3	3	3	[58, 59]

Table 9 is formed as a result of the ease of 3D printing by a multiple filler combination as per the rubric shown in Table1. Table 9 is the basis for paired comparison between various alternatives for multiple fillers. In Table 9 for "Rheological Property" sub-parameter, a rating of 4 is given to SiC/Al2O3 filler and 3 for Flax+Glassveil+Biorez filler. This clearly indicates that more weightage is for SiC/Al2O3 compared to Flax+Glass veil+Biorez. This information would be useful for making a paired comparison between various alternatives. Figure 6 shows that the normalized value for SiC/Al2O3 compared to Flax+Glass veil+Biorez is 0.181, and Flax+Glass veil+Biorez compared to SiC/Al2O3 is 0.136. Similar comparisons are done for all the alternatives and for all the sub-parameters of multiple fillers on the basis of Table 9. Figure 6 shows the normalized results for all the alternatives for multiple fillers.

Table 9 Ratings for various sub-criteria for multiple fillers

	FILAMENT FABRICATION				3D PRINTING		3D PRINTED PART		
	Voids %	Diameter uniformity	Dispersion of fillers	Rheological properties	Nozzle clogging	Interlayer bonding	Part Color	Part surface texture	Ref
CNF+CuO	5	5	5	5	4	4	4	4	[3]
CuO+TiN	5	5	5	5	4	4	4	4	[10]
PLA+Ni-Cu	5	4	4	5	4	4	4	4	[68]
Flax+Glass veil+Biorez	3	3	3	3	4	4	3	3	[30]
SiC/Al_2O_3	4	4	4	4	4	4	3	3	[65]

In 3D printing, the impact of every sub-parameter on the 3D printing process would be different. It is therefore necessary to categorize the subparameters. Different weights have been assigned to various sub-parameters, and they are as listed in Table 10. These weights were estimated using equation (4).

Table 10. Weightage of the criteria for ease of 3D printing

Criteria	Sub Criteria	Weightage (%)
Filament Manufacturing	% Voids in filament	8.1
	Dia. Uniformity	3.6
	Dispersion of filler	33.2
	Rheological properties	22.0
3D printing	Nozzle clogging	5.9
	Interlayer bonding	19.2
3D printed part	Part Color	4.3
	Part surface texture	3.6

The weights assigned to various sub-criteria, as listed in Table 10, were used for natural fillers, synthetic fillers, and multiple fillers.

The consistency between the results of paired comparisons is ensured through the consistency index. It was found that all the comparisons were consistent. In some cases where there were minor inconsistencies, the paired comparison ratings were revised accordingly so as to get the consistency index below 0.1.

After this step, for every sub-criterion, a paired comparison between various alternatives was made. As an example, Table 11 is formed using Table 7 as the baseline using equation (2). The results of paired comparison between various available alternatives for natural fillers for "percentage voids" were calculated and are listed in Table 11. It can be seen from Table 7 that CNC/CNF with a rating of 5 has more weightage on Bamboo, having a rating of 2 for "Dispersion of fillers" sub-criterion. So from Table 11, it can be seen that CNC/CNF, compared to Bamboo, has a score of 2.5, while Bamboo, compared to CNC/CNF, has a score of 0.4.

Table 11. Paired comparison between various alternatives for the sub-criterion "% voids in filament" for natural fillers

% Voids in filament	Harakeke	Hemp	Jute	Flax	Basalt	CNC/CNF	Bamboo	Pine Wood	Kenaf
Harakeke	1	0.8	1	0.75	0.75	0.6	1.5	1	0.75
Hemp	1.25	1	1	0.75	0.75	0.6	1.5	1	0.75
Jute	1	1	1	0.75	0.75	0.6	1.5	1	0.75
Flax	1.333	1.333	1.333	1	1	0.8	2	1.33	1
Basalt	1.333	1.333	1.333	1	1	0.65	2	1.33	1
CNC/CNF	1.667	1.667	1.667	1.25	1.538	1	2.5	1.67	1.25
Bamboo	0.667	0.667	0.667	0.5	0.5	0.4	1	0.67	0.5
Pine Wood	1	1	1	0.752	0.752	0.598	1.493	1	0.75
Kenaf	1.333	1.333	1.333	1	1	0.8	2	1.333	1

In order to have uniform results, the ratings of Table 11 are normalized using Equation (3) and listed in Table 12.

Table 12. Normalized results of paired comparison between various alternatives for the criteria % voids for natural fillers

	Harakeke	Hemp	Jute	Flax	Basalt	CNC/CNF	Bamboo	Pine Wood	Kenaf	Final Score
Harakeke	0.095	0.079	0.097	0.097	0.093	0.099	0.097	0.097	0.097	0.094
Hemp	0.118	0.099	0.097	0.097	0.093	0.099	0.097	0.097	0.097	0.099
Jute	0.095	0.099	0.097	0.097	0.093	0.099	0.097	0.097	0.097	0.097
Flax	0.126	0.132	0.129	0.129	0.124	0.132	0.129	0.129	0.129	0.129
Basalt	0.126	0.132	0.129	0.129	0.124	0.107	0.129	0.129	0.129	0.126
CNC/CNF	0.158	0.164	0.161	0.161	0.191	0.165	0.161	0.162	0.161	0.165
Bamboo	0.063	0.066	0.064	0.065	0.062	0.066	0.065	0.065	0.064	0.064
Pine wood	0.095	0.099	0.097	0.097	0.094	0.099	0.096	0.097	0.097	0.097
Kenaf	0.126	0.132	0.129	0.129	0.124	0.132	0.129	0.129	0.129	0.129

The normalized scores for all the alternatives for various sub-criteria of natural fillers are shown in Figure 4. It is clearly evident that CNC/CNF has the highest rating among the natural fillers, which is followed by Jute fiber and basalt fillers, which becomes a probable option to be chosen as fillers for the filament for FDM 3D printing. Bamboo fiber and pine wood are amongst those that have the lowest ratings, which indicates that they are not very suitable as a natural filler.

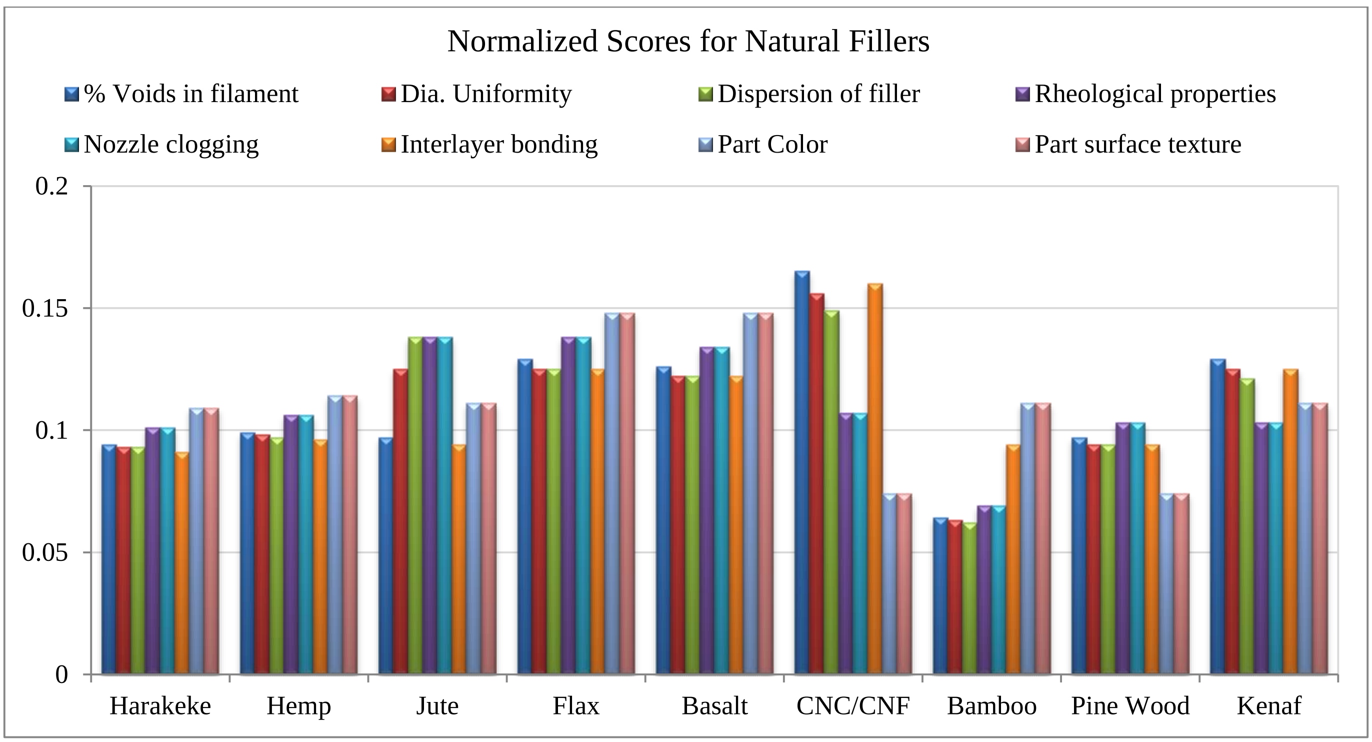

Fig. 4 Normalized scores for various sub-criteria of natural fillers

The same method was applied for all the sub-criteria for natural fillers, Synthetic fillers and for multiple fillers. The normalized score for all the alternatives for synthetic fillers is shown in Figure 5. It is clear that Graphene and MWCNT show higher normalized scores, followed by short glass fiber and Al_2O_3. These are suitable alternatives to the polymer filament for FDM 3D printing. Zeolite, ZrB_2 and Montmorillonite have a very low normalized score, so they appear to be non-suitable alternatives for the polymer filament for FDM 3D printing.

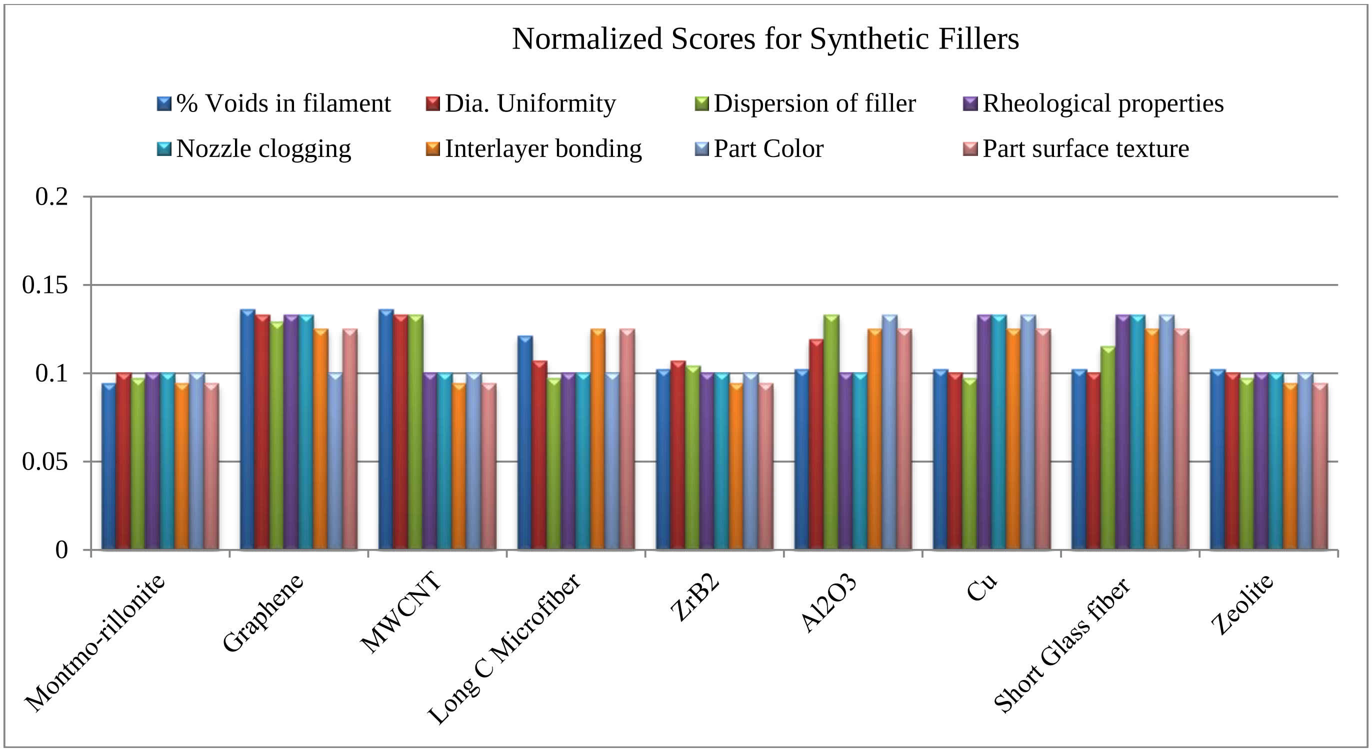

Fig. 5 Normalized scores for various sub-criteria for synthetic fillers

Figure 6 gives the normalized scores of multiple fillers. CuO+CNF have the highest rating, so it is a suitable alternative to be used as fillers in polymer filament for FDM 3D printing. CuO+TiN and Ni+Cu also show suitable alternative but Flax+Glass veil+Biorez does not seem to be a suitable alternative as a multiple filler for polymer filament for FDM 3D printing, owing to its low sore of paired comparison.

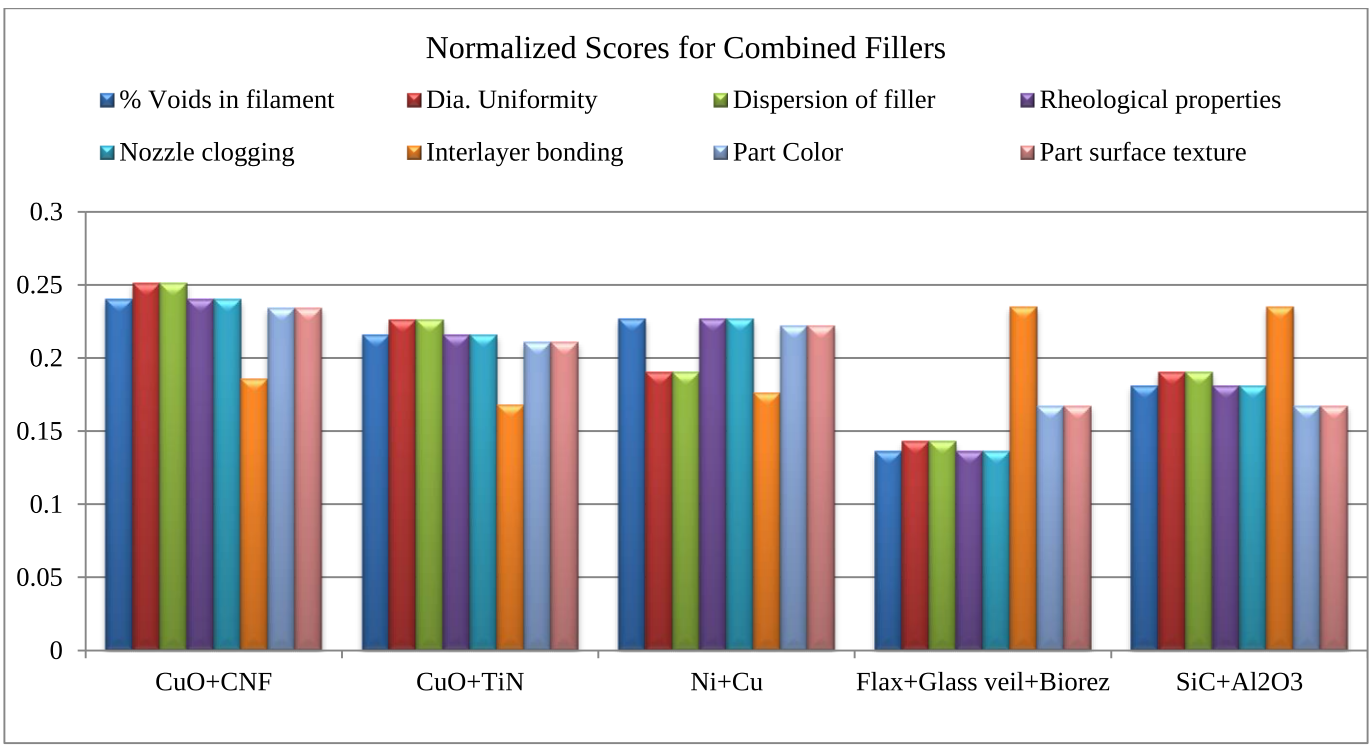

Fig. 6 Normalized scores of various sub-criteria for multiple filler

As per Table 10, various sub-criteria have been given some weight based on their importance. In order to get the final rating of the alternatives, sub criteria wise weighted score of an alternative is estimated. These results are listed in Tables 13, 14 and 15 for natural fillers, synthetic fillers and multiple fillers, respectively.

4. Results and Discussion

Table 13 gives the final score of various alternatives for natural fillers based on the weights of sub-criteria calculated using equation (5). It is evident that Cellulose Nano Fibril (CNF)/ Cellulose Nano Crystals (CNC) with a final score of 0.135 is the first preference to be used as filler, so as to have ease of 3D printing through natural fillers in the composite filament. Flax fiber is the second option for composite filament, with a final score of 0.13, while basalt fiber is the third option with a score of 0.128. It is found that the improvement in properties is due to reinforcing effects, improved crystallinity, and better interfacial bonding between the filler and the matrix [6, 37] when used at optimum levels of filler loading.

Table 13. Final rating of various alternatives for natural fillers

Summary	% Voids in filament	Dia. Uniformity	Dispersion of filler	Rheological properties	Nozzle clogging	Interlayer bonding	Part Color	Part surface texture	Final Score
Harakeke	0.094	0.093	0.093	0.101	0.101	0.091	0.109	0.109	0.096
Hemp	0.099	0.098	0.097	0.106	0.106	0.096	0.114	0.114	0.101
Jute	0.097	0.125	0.138	0.138	0.138	0.094	0.111	0.111	0.123
Flax	0.129	0.125	0.125	0.138	0.138	0.125	0.148	0.148	0.130
Basalt	0.126	0.122	0.122	0.134	0.134	0.122	0.148	0.148	0.128
CNC/CNF	0.165	0.156	0.149	0.107	0.107	0.160	0.074	0.074	0.135
Bamboo	0.064	0.063	0.062	0.069	0.069	0.094	0.111	0.111	0.074
Pine Wood	0.097	0.094	0.094	0.103	0.103	0.094	0.074	0.074	0.095
Kenaf	0.129	0.125	0.121	0.103	0.103	0.125	0.111	0.111	0.117

Table 14 gives the final score for synthetic fillers. For ease of 3D printing with synthetic fillers, graphene is the first option to be used as filler in composite filament for FDM 3D printing, with a score of 0.128. Short glass fibers are the next option for FDM 3D printing, with a score of 0.121, while Al2O3 becomes the third option as filler for composite filament. The results of the sensitivity analysis conducted by changing the weights of the criteria are shown in Table 14. It is clear from the sensitivity analysis that the best filler remains the same. Similar analysis is done for natural fillers and multiple fillers. The improvement due to the addition of graphene is mainly due to the high surface area provided, which results in a strong interfacial stress transfer network [9, 55, 70].

Table 14. Final rating of various alternatives for synthetic fillers

Summary	% Voids in filament	Dia. Uniformity	Dispersion of filler	Rheological properties	Nozzle clogging	Interlayer bonding	Part Color	Part surface texture	Final Score	Sensitivity Analysis Score
Montmo-rillonite	0.094	0.100	0.097	0.100	0.100	0.094	0.100	0.094	0.097	0.076
Graphene	0.136	0.133	0.129	0.133	0.133	0.125	0.100	0.125	0.128	0.153
MWCNT	0.136	0.133	0.133	0.100	0.100	0.094	0.100	0.094	0.114	0.118
Long C Microfiber	0.121	0.107	0.097	0.100	0.100	0.125	0.100	0.125	0.107	0.102
ZrB2	0.102	0.107	0.104	0.100	0.100	0.094	0.100	0.094	0.100	0.081
Al2O3	0.102	0.119	0.133	0.100	0.100	0.125	0.133	0.125	0.119	0.129
Cu	0.102	0.100	0.097	0.133	0.133	0.125	0.133	0.125	0.115	0.123
Short Glass fiber	0.102	0.100	0.115	0.133	0.133	0.125	0.133	0.125	0.121	0.142
Zeolite	0.102	0.100	0.097	0.100	0.100	0.094	0.100	0.094	0.098	0.074

Table 15 gives the final score of multiple fillers for filament for FDM 3D printing from the perspective of ease of 3D printing. Cuprous Oxide and Cellulose Nano Fibril combination is the best suited alternative amongst the given alternatives, with a score of 0.233, while Cuprous Oxide and Titanium Nitride is the second best alternative with a score of 0.210. The combination of Copper and Nickel is the third alternative with a score of 0.203. The improvement in strength due to cuprous oxide is mainly attributed to Nano reinforcement, increased crystallinity and enhanced interfacial interaction [3, 10].

Table 15. Final rating of various alternatives for multiple fillers

Summary	% Voids in filament	Dia. Uniformity	Dispersion of filler	Rheological properties	Nozzle clogging	Interlayer bonding	Part Color	Part surface texture	Final Score
CuO+CNF	0.240	0.251	0.251	0.240	0.240	0.186	0.234	0.234	0.233
CuO+TiN	0.216	0.226	0.226	0.216	0.216	0.168	0.211	0.211	0.210
Ni+Cu	0.227	0.190	0.190	0.227	0.227	0.176	0.222	0.222	0.203
Flax+Glass veil+Biorez	0.136	0.143	0.143	0.136	0.136	0.235	0.167	0.167	0.160
SiC+Al2O3	0.181	0.190	0.190	0.181	0.181	0.235	0.167	0.167	0.194

5. Conclusion

For selecting the fillers for ease of FDM 3D printing, AHP was successfully incorporated. Three different criteria, categorized into eight different sub-criteria, were considered for ease of 3D printing. Three different scenarios, which include natural fillers, synthetic fillers and multiple fillers, were employed. The top three alternatives are tabulated in Table 16 based on their weightage and final score.

Table 16. Top 3 fillers under each category

Rank	Filler	Score
Natural Filler		
Rank	**Filler**	**Score**
1	Cellulose Nano Fibril (CNF)/ Cellulose Nano Crystals (CNC)	0.135
2	Flax	0.13
3	Basalt	0.128
Synthetic Filler		
Rank	Filler	Score
1	Graphene	0.128
2	Short Glass fibers	0.121
3	Alumina (Al2O3)	0.119
Multiple Filler		
Rank	Filler	Score
1	Cuprous Oxide and Cellulose Nano Fabril	0.233
2	Cuprous Oxide and Titanium Nitride	0.210
3	Copper and Nickel	0.203

Using PIF, the alternatives that contributed to enhancing Mechanical, Thermal and Rheological properties were shortlisted, which means that these fillers also contribute to improving these properties along with ease of 3D printing when used in polymer filament. When using a single filler for enhancing the Mechanical properties, it is found that graphene is a suitable alternative. It can be concluded that graphene is not only suitable for enhancing the mechanical properties, but also does not negatively affect the 3D printing process when used at optimum loading levels. Similarly, CNC/CNF has been found to improve the mechanical properties, and it can be concluded that it does not negatively affect the 3D printing process when used as reinforcement in polymer filament. When multiple fillers are used, Cu_2O and CNF combination gives better properties for 3D printing. As the baseline for the paired comparison is made referring to the research work where the mechanical properties were enhanced and 3D printing was done without much issue, the results obtained are in good agreement with existing literature. From a sustainability perspective, CNC/CNF is particularly attractive due to their renewable, biodegradable, and bio-based origin, making them suitable for the development of environmentally friendly composite filaments with a reduced carbon footprint. The incorporation of such natural nanofillers can contribute to the advancement of sustainable additive manufacturing practices while reducing dependence on petroleum-derived reinforcement materials.

Future Scope

The results of the Analytic Hierarchy Process (AHP) revealed that Graphene Nanoparticles (GNPs) achieved the highest ranking among synthetic fillers, while Cellulose Nano crystals/Cellulose Nano fibers (CNC/CNF) emerged as the most promising natural fillers. Furthermore, the combination of Cuprous Oxide and CNF demonstrated superior potential among hybrid filler systems. Future work should focus on experimentally validating these rankings through the fabrication and characterization of PLA-based composite filaments reinforced with the identified fillers and filler combinations. Detailed investigations on the effects of filler loading, dispersion quality, interfacial bonding, rheological behavior, thermal stability, and mechanical performance of

FDM-printed specimens can be conducted. In particular, hybrid reinforcement using GNP and CNC/CNF offers significant potential to synergistically enhance stiffness, strength, thermal resistance, and sustainability. The experimental outcomes can then be compared with the AHP-based predictions to assess the reliability of the decision-making framework and establish optimized filler systems for high-performance and sustainable FDM 3D printing applications. Although GNPs offer superior mechanical and thermal enhancement, future studies should evaluate their performance-to-cost ratio and environmental impact throughout the material life cycle. Furthermore, techno-economic analyses can be conducted to assess the commercial feasibility of large-scale filament production using GNP, CNC/CNF, and hybrid filler systems. Such investigations will help identify filler combinations that not only provide enhanced performance but also achieve an optimal balance between sustainability, material cost, process ability, and industrial applicability for next-generation FDM 3D printing applications.

Authors' Contribution Statement:

All Authors have equal contributions.

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