



## A Review on Green Composites

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### Abstract

Composites are most widely used materials as they can provide specific advantages and can relatively easily combine with other materials exhibiting desired properties. Various composites like nanocomposites, matrix composites, composites augmented using diversified fibers etc. do commonly utilized towards discrete sapphires. Environmentalist amalgamation considered to be unmistakable grade with regard to natural amalgamation at which point natural fibers combine with natural resins to make light and strong composites. The present paper studies green composites, encompassing thermosetting and thermoplastic variants. It focuses on the selection of an appropriate polymer matrix and natural-organic filler for a given polymer. In the field of environmentalist amalgamation already utilized matrixes, raw plus pure fibrils, surface modification methods [physical and chemical modifications] and methods of preparation of green composites are also discussed in this paper.



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### Abbreviations

**PMC:** Polymer Matrix composite  
**ROM:** Rule of Mixtures  
**PDS:** Product Design Specification  
**PLA:** poly lactic acid  
**PHA:** polyhydroxyalkanoate  
**PNS:** Peanut Shell  
**UPR:** Unsaturated polyester Resin  
**BC:** Bacterial Cellulose  
**CNSL:** Cashew Nutshell Liquid  
**RH:** Rice Husk  
**PCL:** poly caprolactone

**MAgPP:** polypropylene implanted through Maleic anhydride

**MAgEPDM:** Maleic anhydride grafted ethylene propylene diene copolymer

### Introduction

Polymer composites have been widely used for several years<sup>1</sup> plus for turning events and utilizations of harmless to ecosystem economical polymer amalgamation with goal that their market share can grow continuously; many exploration endeavors have been made.

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Intensifying temperature on earth surface and use of non-biodegradable materials lead to increase in global warming.<sup>2</sup> That's why there is a need for Green and eco-friendly materials which have been considered as high efficiency, inexpensive, lightweight nanocomposites. Scientists' advantage has been expanded in finding polymer amalgams loaded up with normal biological fillers because of rising worry towards ecological issues.<sup>3</sup> The nanocomposites based on eco-friendly polymers and eco-nanofillers are usually termed as Green Polymeric nanocomposites.<sup>4-5</sup>

Critical exploration has been led prompting improvement in natural amalgams with high strength which may named as progressed green amalgams.<sup>6</sup> So, the endeavor towards this path ought to be centered on creation of polymer composites in light of post-consumer polymers loaded up with regular fillers for example strands separated from plants.<sup>1</sup>

Normal natural fillers are extremely modest; furthermore significantly less confrontational as well as less destructive because they permit decrease being used of non-sustainable assets in light of the fact that they are generally abstracted using plants.<sup>1</sup>

Best plus extensively utilized normal natural fillers embraces- timber powder, nut shell dust, grain husk powder, semolina pods, filament husk, maize-colt powder, cock plumes, spigot flour, wood fiber, cotton flax, sisal, kenaf, jute, hemp, starch etc.<sup>7-10</sup>

Plant based natural amalgations have drawn in enormous exploration interest because horticultural assets/squanders or items are being utilized for creation of natural amalgations.<sup>11</sup> Through synergistic impact of eco-accommodating plus green supporting nanofillers, numerous useful properties, natural neighborliness as well as biodegradability of green nanocomposites can be accomplished.<sup>4</sup>

This audit has been created taking into account the significance of green composites<sup>4</sup> zeroing in on natural organic fillers, sustainable polymer matrices, nanofillers in order to get green composites.

### **Waste Recycling in Green Materials**

In the context of sustainable material development, waste recycling plays a pivotal role in achieving a circular economy and reducing environmental

footprints. The increasing generation of post-consumer plastic waste and agricultural residues necessitates their value-added reuse in polymer composite systems. Recycled materials offer a dual advantage: reducing the environmental burden and lowering the cost of raw materials. Recent studies have demonstrated that incorporating recycled waste—such as polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP)—into polymer matrices can result in composites with enhanced mechanical and thermal properties.<sup>12, 13</sup>

Furthermore, agricultural byproducts such as rice husk, coconut coir, flax fibers, jute, sisal, kenaf, and cotton waste have been identified as promising fillers in green composites.<sup>14, 15</sup> These natural fillers not only improve the biodegradability and environmental compatibility of the composites but also contribute to the reduction in carbon emissions and landfill load. For instance, wood flour, nutshell powder, and maize husk have been effectively used as reinforcements to develop biodegradable polymer composites with favorable mechanical strength and water resistance.<sup>16, 17</sup>

Recent advances also highlight the feasibility of using industrial agro-waste like bagasse, oil palm fibers, and wheat straw as reinforcement in bio-based polymer systems.<sup>18, 19</sup> Such efforts help mitigate the problems related to agro-waste disposal while enhancing the sustainability of composite materials. Moreover, thermoplastic recycling of post-consumer polymers and their reinforcement with lignocellulosic fillers has shown great promise in producing robust and cost-effective green composites.<sup>20, 21</sup>

Innovative processing techniques, including extrusion, compression molding, and solvent casting, have further facilitated the integration of recycled waste into green composites. Some researchers have explored hybrid reinforcement systems, combining both recycled polymers and natural fibers to maximize performance and biodegradability.<sup>22, 23</sup> These strategies are aligned with global goals to reduce dependency on virgin materials and promote eco-innovation in composite manufacturing.<sup>24</sup>

Thus, waste recycling in green composites is not merely a sustainability tactic but a vital engineering

strategy aimed at enhancing material functionality while addressing urgent ecological challenges.<sup>25-27</sup>

**Scientific Gap and Objectives of the Study**

Despite the significant strides in green composite development, a scientific gap remains in the comprehensive understanding of the synergistic effects between sustainable polymer matrices, natural organic fillers, and eco-friendly nanofillers. Existing literature tends to focus on individual components—such as the use of natural fibers or biodegradable polymers—but lacks integrative studies that explore the full potential of multifunctional green nanocomposites.<sup>15, 22</sup>

Moreover, there is limited exploration of the role of recycled materials in enhancing the structural and functional attributes of polymer composites. While numerous works have confirmed the potential of post-consumer plastics and plant waste as raw materials, the interactions between their chemical structure, interfacial compatibility, and composite morphology are still underexplored.<sup>28, 29</sup> For instance, there is a need to investigate how surface modification of natural fillers and nanoparticles can improve dispersion and adhesion in recycled polymer matrices to optimize composite properties.<sup>30</sup>

Additionally, while nanofillers such as nanocellulose, montmorillonite, nano-silica, and graphene oxide have shown potential to enhance mechanical strength, barrier properties, and biodegradability, their combined effect with recycled biopolymers and agro-waste-based fillers remains inadequately

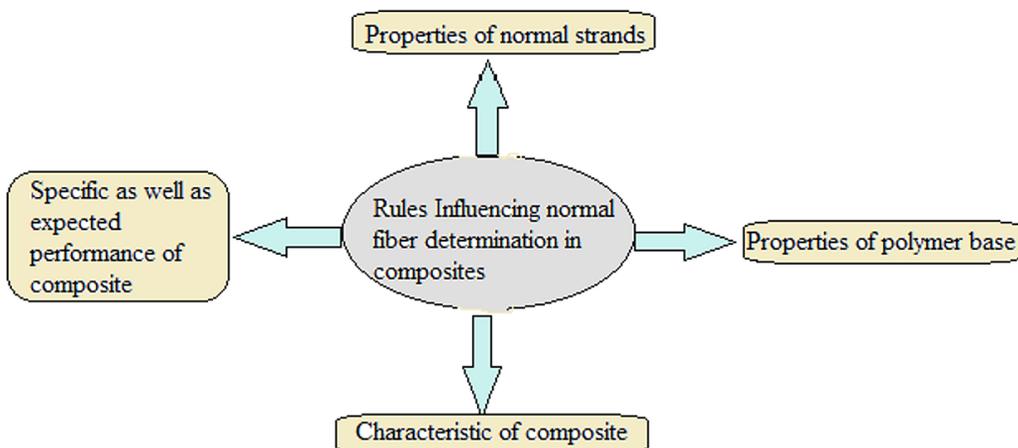
documented in current research.<sup>17, 21, 24</sup> There is also a lack of standardized evaluation parameters to measure the environmental impact, lifecycle, and end-of-life behavior of such hybrid composites.

Therefore, this review aims to bridge this knowledge gap by focusing on the development of green composites comprising (i) bio-based and biodegradable polymers, (ii) recycled waste-derived components, (iii) natural organic fillers, and (iv) eco-friendly nanofillers. The objective is to provide a comprehensive outlook on material design strategies, synthesis approaches, property enhancement mechanisms, and the potential applications of such composites, while highlighting recent innovations and challenges in the field.

**Green Composites**

Up and coming age of practical composite substances are said to be green composites<sup>12</sup> and the important class of organic based composites where both grid plus support get from sustainable assets, also explored widely due to their intensified properties. Hence, one may get well built composite which are reusable or reclaimable through activate. The belongings of normal strands utilized in support directly influence presentation of green composites.<sup>13</sup>

Selecting natural fibers, amidst certain accessible in nature as support related to provided polymer, is directed through upsides of composite's solidness and powerfulness required.<sup>14</sup> However, selection of natural fibers in PMC depends upon various factors (figure 2.1) and can be represented as<sup>15-16</sup>:-



**Fig.2.1: Guidelines for determining typical fibres in composites**

Choice of fitting framework for polymer lattice composite in view of expected utilization is basic undertaking since the last property of composite is straightforwardly impacted by network used.<sup>16-17</sup>

Based on previous study, natural fiber and polymer matrix is selected using statistical analysis.<sup>18</sup> A novel statistical framework was introduced by Noryani *et al.* 2019. The overall methodology involves following steps and the complete process displayed in (figure 2.2):-

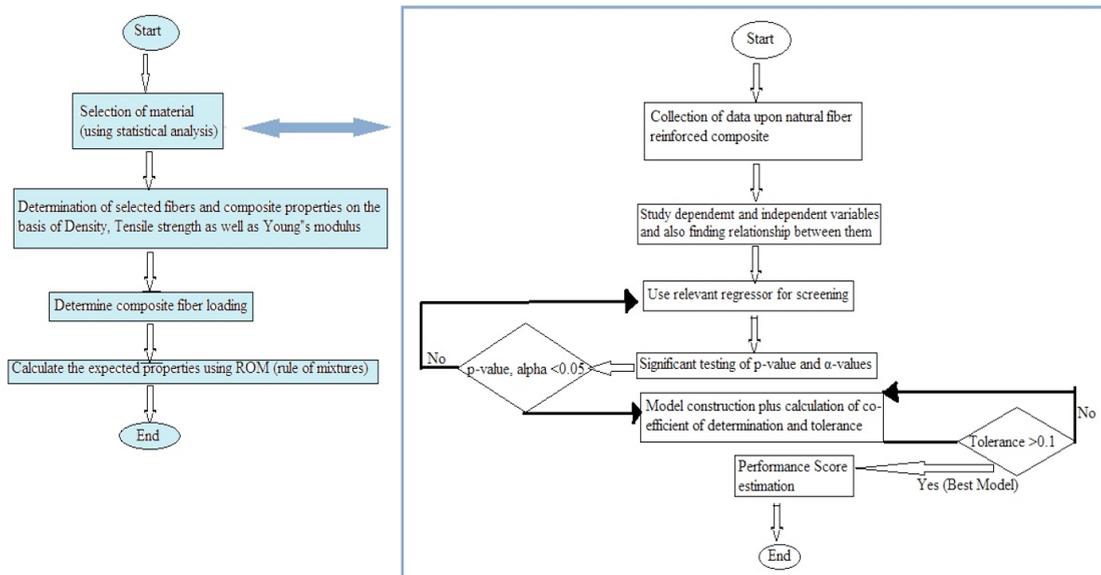
(I) Material is selected using statistical analysis.

- First collect data on natural fiber reinforced composite.
- Study on dependent and independent variables.
- Then, study the relationship between the variables.

- Fourthly, screening is done with a relevance regressor.
- Significant testing of p-value and  $\alpha$ -values. If these values  $<0.05$  then construct a statistical model, if not then exclude the variable.
- After constructing a statistical model, calculate the coefficient of determination and tolerance. If tolerance  $>0.1$  then it will be the best model of composite.
- At last, estimate the performance score for composite judgment and select the material.
- Determine the selected fiber and matrix properties (like density, young's modulus, tensile strength) based on PDS.

(III) Determine composite fiber loading.

(IV) Calculate the expected properties using ROM.



**Fig.2.2: Flowchart displaying the complete process<sup>18</sup>**

Thermoset and Thermoplastic based resins is the classification of Matrix material which can be used in polymer matrix composite. So, based on this, we may have two types of green composites.<sup>14</sup>

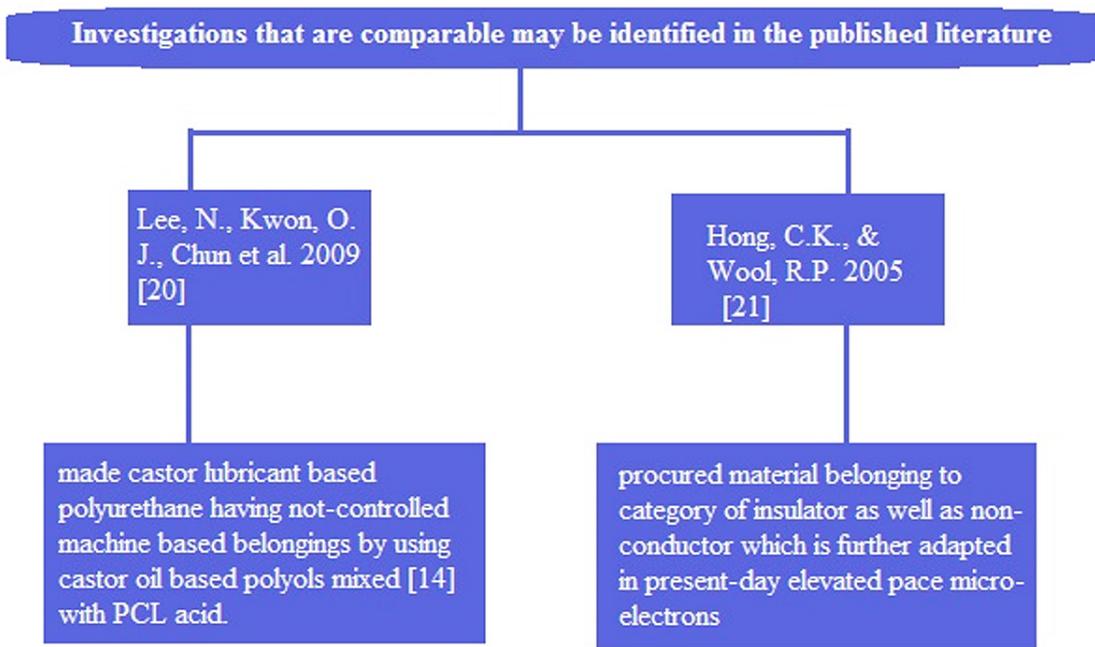
### Green Composites Related to Thermosets

Already familiar that petrochemical-derived thermosetting resin wax (irreversibly cures) such as vinyl esters, polyesters, epoxy plus polyurethane adhesives are replaced by utilizing normal oils like

coconut lubricants, shea butter oil, soybean, castor oil.<sup>19</sup> Natural oils are composed of molecules known as triglycerides (an ester derived from glycerol and fatty acids) and polymerization of oils can be done by addition of chemical functionalities like ester Group, double bond etc. on their active sites. Some methods used in functionalizing unsaturated plant oils are ozonolysis, epoxidation, reaction of ring opening using alcohols or halo acids plus hydration<sup>19</sup> and commonly used resins are polyurethane prepared

using anhydrides, diisocyanates from petrochemical feedstock plus normal polyols. Two studies related to thermosets are displayed in figure 2.1.1 below:

Green composites relating to thermosets not so far procured remarkable construction volume because of shortage of satisfactory natural thermosets.<sup>14</sup>

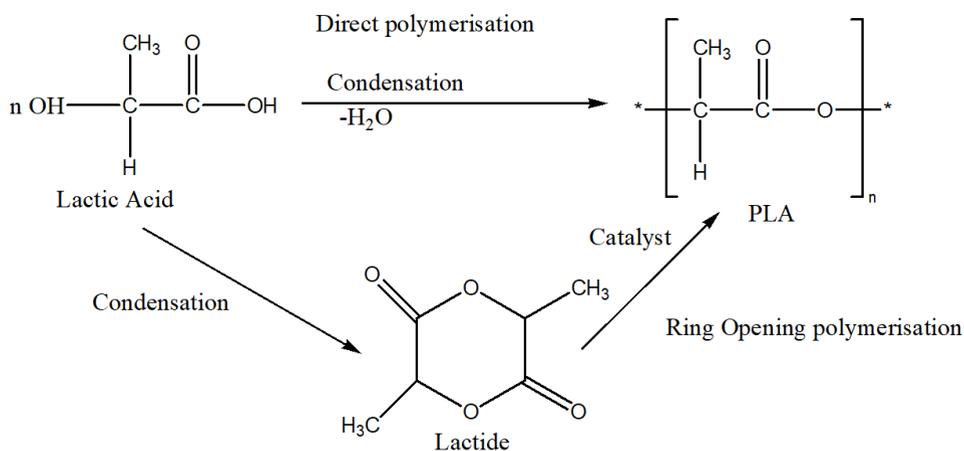


**Fig.2.2: Comparable published literature related to thermosets<sup>20-21</sup>**

**Thermoplastic Green Composites**

Poly-lactic acid (thermoplastic based monomer) can be obtained using natural origins like maize, polysaccharide or sugarcane [i.e. Starch fermentation]. Tasks done on Poly-lactic acid related green amalgations are lately evaluated alongside Roberto scaffaro *et al.*<sup>22</sup>

Bajpai *et al.*<sup>14</sup> reviewed development and characterization as concerns green composites related to poly-lactic acid. Figure 2.2.1 shows the formulation of poly-lactic acid:



**Fig.2.2: Production process of PLA can be displayed as<sup>14</sup>**

Thus until the present time, a number of PLA based amalgations supported through normal strands are introduced in character of PLA is an environmentally, plant derived thermoplastic.

Besides PLA, examinations on utilization of polyhydroxyalkanoates in character of lattices are extremely taken into account. These are naturally occurring biodegradable polymers plus polyesters obtained normally through action of microbe including through bacilli ferments of maltose, dextrose, triglyceride, lipide etc. Many review papers are there which present tasks already being finished related to polyhydroxyalkanoates based bio-composites like.<sup>23</sup>

In contrast to thermosetting composites, thermoplastic Green composites (due to techniques of manufacturing), only bounded strand filling be procured.

### Polymer Matrices used in Field of Green Amalgations

Polymer framework decides frequent recyclable cycles and it is ceaseless stage in amalgations utilized to hold supporting specialist in its place. In sphere of green composites, frequently used polymer lattices are given below<sup>24</sup>:-

#### Polyethylene

Polyethylene is a member of an important family of polyolefin's resins. Polymer composites based on biodegradable polymers.<sup>1</sup> To improve polymer-particle interaction, PE-g-MA derived from bio-based polyethylene and PNS flour was used on green composites.<sup>25</sup> Composites of peanut shell grounded high density polyethylene having 10wt% peanut shell powder congenial zed alongside 3wt% of PE-g-MA.<sup>25</sup> Different fillers that can be utilized in polyethylene based composites are displayed in table 3.1.1.

**Table 3: Various reinforcements (fillers) utilized in composites based on (C2H4)n**

COMPOSITE	FILLER	REFERENCE
<b>Polyethylene based composite</b>	Wood chips and cellulosic fibers	26, 27
	Corn starch	28
	Sago starch	29, 30
	Sisal fiber	31

Furthermore, many papers report post-consumer recycled polyethylene<sup>32, 33</sup> which used timber strands plus milk decanters containing high-density polyethylene<sup>1</sup> as well as from food containers and also from green-house films.

#### Polyester Resin

Higher volume produced polyester is PET which is a saturated polyester but recycled PET can give unsaturated polyester resins which is commonly used in preparing composites.<sup>34, 35</sup> Production technique of UPR-wood flour composites involve following steps (displayed in figure 3.2.1).

Other examples of polyester based composites<sup>36</sup> inculcates Jute fiber augmented inmost polyester

lattice stuff can be utilized for erroneous ceilings of households;<sup>36</sup> Coir and polyester based composite materials are used in preparing post boxes, roofing panels etc.; Banana strand augmented polyester plus epoxy amalgations are utilized for evolving lantern plus many more galvanic appliances.<sup>36</sup>

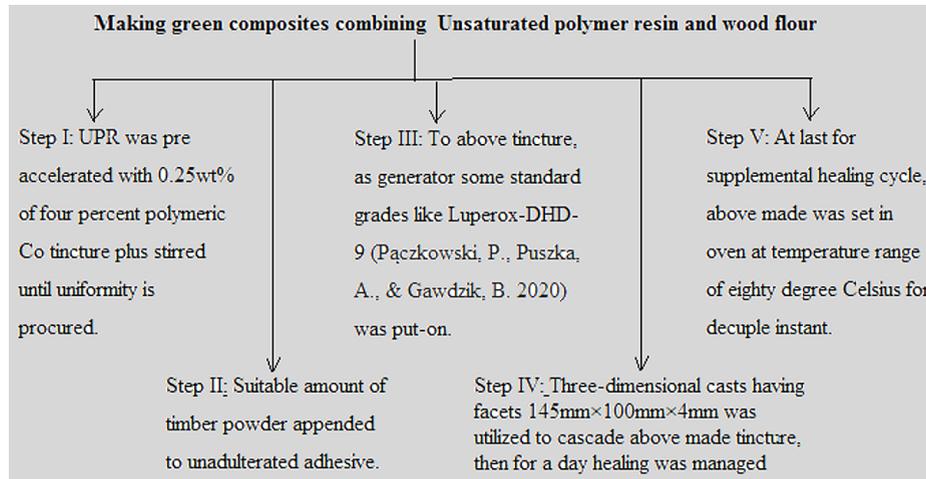
Polyester amalgations supported with woodchips<sup>37</sup> already made through inclusion of alkali treated and untreated feedstock to polyester then cross-joining reaction was carried out, finally already made amalgation was antidote at increased temperature.

#### Epoxy Matrices

Epoxy resin has very good adhesive properties, additional invulnerability for tiring, rupturing plus

striping in addition to destruction from chemicals as well as climatic mortification. One key divergence of

polyester paste in comparison with epoxy paste is related with their adhering belongings.



**Fig.2.2: Preparation of green composites using UPR and wood flour<sup>35</sup>**

Examples of normal strand composites prepared using epoxy lattice<sup>36</sup> may includes Epoxy lattice substance supported through cord strands are utilized in manufacturing of sailing-boat hills<sup>36</sup>; Normal strand amalgations prepared utilizing epoxy lattice already utilized in creation of barrels for numerous machine-driven functions.<sup>36</sup>

From warm-healing cycle, through utilization of methylhexahydrophthalic anhydride denser<sup>38</sup>, epoxy wax based BC (Bacterial Cellulose) can be acquired.

**Phenolic Filaments**

Phenolic tar manifests squat degree of intensity opposition while epoxy tar conveys elevated degree of intensity obstruction which is only vital distinction between phenolic and epoxy tar moreover epoxy tar is comparatively used for a long time than Phenolic resin. Phenolic resin can be related to category of thermosetting tars framed through build up of a phenol subordinate or phenol itself plus aldehyde, particularly formaldehyde.

In midst of composite spheres for primary strength plus non-underlying solidness functions, phenolic tars are very conspicuous polymers.<sup>39</sup>

Strength stiffness is given to structure by fibers which are working as reinforcement in fiber-

reinforced composites while polymer manages tenacity plus holding strand set-up with the goal that reasonable underlying parts can be made.<sup>39-40</sup> Detailed concentrate on phenolic based composites involving different reinforcements is present in table 3.4.1.

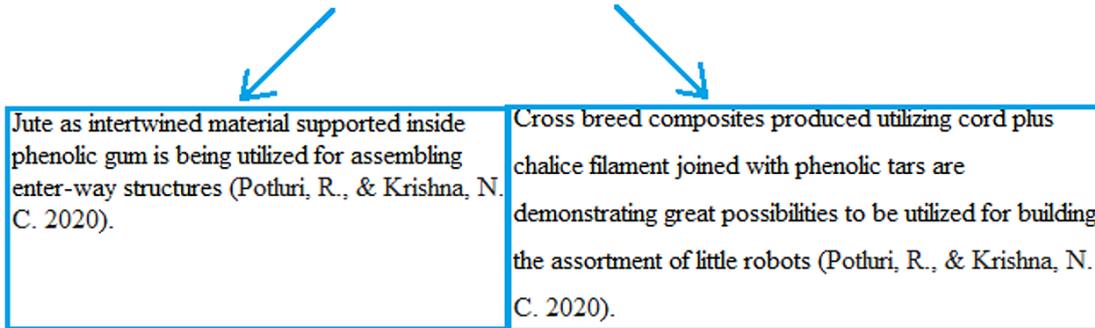
Goto plus co-workers<sup>41</sup> designed high level synthetic reusing cycle that basically centered around phenolic gum yields interestingly.

There are various applications shown by natural fiber Phenolic composites such as in sports applications [golf clubs, tennis rackets], in aircrafts, transportation, chemical equipment, fishing rods, storage tanks.

**Table 3.4.1: inspired by<sup>39-40</sup> related to detailed concentrate on regular strands built up Phenolic composites**

PHENOLIC TAR	REINFORCEMENT (Filler)
Phenol based CNSL	Hemp fiber
Phenol based CNSL	Sisal fiber
Phenol formaldehyde	Oil palm fiber
Phenolic Resin	Jute fiber

**Other examples (Potluri, R., & Krishna, N. C. 2020<sup>36</sup>)**



Jute as intertwined material supported inside phenolic gum is being utilized for assembling enter-way structures.<sup>36</sup> Cross breed composites produced utilizing cord plus chalice filament joined with phenolic tars are demonstrating great possibilities to be utilized for building the assortment of little robots.<sup>36</sup>

**Polypropylene**

There are many papers which reveal a few examinations on polypropylene in blend with cartridge like rattan, cord, timber, cannabis sativa, polysaccharide etc. and many fascinating outcomes have been found in regards with impact of these fillers upon mechanical, solidification, morphological properties of propylene hinged conglomerate.<sup>1</sup>

Certain illustrations are appeared in writings<sup>1</sup> regarding SiH4-hinged mixtures, MAgPP, MAgEPDM

etc. This allowed significant improvements of mechanical and morphological properties.

**Supplementary**

Instances of exploration on regards to different sorts of polymer lattices in mix with other regular natural supporters<sup>1</sup> includes PLA based composites,<sup>13, 42</sup> PHA based composites,<sup>23</sup> PCL, Phenolic resin and several natural fibers,<sup>43</sup> sisal fiber and polystyrene.<sup>8</sup>

**Filaments Utilized in Sphere of Lush Compounds**

Green composites perhaps divided into three main types on the basis of type of reinforcement and polymer matrices<sup>44</sup>:-

**Classification of Green Composites: (Table 4.1.1)**

Organic fillers are variety of natural solid fibers and particulates that can be used in reasonably large volume loadings in polymer matrices.

**Table 4.1: Classification of green amalgations hinged on kind of network and support utilized in composite's formation**

(I) When network and support are procured from sustainable sources	Totally sustainable composite.
(II) When network got from inexhaustible and built up with manufactured material	Slightly sustainable composite.
(III) Engineered lattice built up with normal bio-polymer	Partially sustainable composite.

**Natural Fibers<sup>20</sup>**

Different plant based and animal based natural reinforcements are given in table 4.2.1.

Regular filaments are primarily made of three head part:- hemicellulose, lignin plus cellulose where hemicellulose adds to representation of normal strand though cellulose is liable for intrinsic

toughness as well as dependability of regular filaments also consider as significant part.<sup>46</sup>

Just like timber- a sinewy compound is normally utilized as wood mash similarly unadulterated filaments are to be produced plus isolated to be utilized as support.<sup>14</sup>

### **Most Extensively used Natural Fibers are Bast Fibers**

Availability of large quantities of Bast filament relies on geological sphere of development. In calm districts, cannabis sativa plus cord are predominant while in tropical locales utilization of kenaf as well as jute wins.<sup>14</sup>

Jute is the cheapest fiber. With no harm to jute belongings, it stays firm up to two hundred degree Celsius also its particular absolute value moves toward that of glass filament.<sup>46</sup>

Cannabis sativa (hemp) is product of cannabis weed group of plant. Flax filaments can be effortlessly intertwined into various kinds of texture when they are utilized to generate composites with various possessions as it is most seasoned fiber crop on the planet.<sup>46</sup>

### **Leaf Fibers**

Leaf fibers like Banana strand augmented polyester plus epoxy amalgations are utilized for evolving lantern plus many more galvanic appliances<sup>36</sup> likewise Normal strand amalgations prepared utilizing epoxy lattice already utilized in creation of barrels for numerous machine-driven functions.<sup>36</sup>

### **Coir**

Coir, likewise said to be coco-strand separated from external hull of coco.<sup>47</sup> The hull (caparison) of cocoa comprises of sheen impermeable superficial derma (peel) plus stringy tract (mesocarp). Coir strand medicated with two percent of antacid was utilized to support polyester conglomeration<sup>48</sup> materials which are used in preparation of post boxes, roofing panels etc. Coir filament is particulars are generally utilized in assembling of rumps for trains, buses, trucks and so on.<sup>36</sup> Coir is additionally moderately water safe plus impervious to salt water harms.<sup>46</sup>

### **Bamboo**

Bamboo is quickly developing grass.<sup>46</sup> The usage of bamboo filaments as support in conglomeration stuff has expanded colossally as well as gone through cutting edge transformation as of late<sup>49</sup> because it has high inherent strength and temperature stability. Specialists created bamboo supported polyester conglomerations by hand-rest-up procedures, also mercimerised the bamboo filament supported epoxy conglomerations, Phenolic-mucilage hinged bamboo

filament supported conglomerations, polypropylene hinged bamboo filament supported compounds, PVC plus polystyrene hinged bamboo filament supported composites are already familiar.<sup>50</sup>

### **RH (Rice Husk) as a Fiber**

Rice is a staple crop of India. Rice husk is ordinarily extreme, woody, water indissoluble plus destructive opposition conduct. Using Rice-Husk as supporter can work on specific machine-based, warm as well as actual belongings. The properties of composites like polypropylene, polyethylene etc. can be enhanced through therapy of Rice-Husk filaments using various methods<sup>51</sup>. Rice-Husk bio-hinged conglomerations can be utilized as trade for timber.

### **Corn Husk**

The disposable corn husk is used as reinforcement. The domestic waste generates lots of corn husk. It is free from dust and other foreign particles. If there are any dust particles or other foreign particles, it should be cleaned or washed and then dried under the sun. The composites are prepared by drying the corn husk and treating it chemically to make it compatible with polymer matrix and then chopped to reinforce it into polymer matrix using hand lay-up method.<sup>52</sup>

### **Wood Flour and Fibers**

Timber powder plus filaments are extensively familiar as well as broadly utilized regular-natural supporters<sup>53</sup> due to minimal expense, layered structure and versatile absolute value. From sawmill squanders; timber filaments can be effortlessly acquired which further can be utilized for screening. Wood strands are delivered through warm machine-based cycles on timber squander.<sup>1, 54</sup> Mixture conglomerations produced utilizing a mix of glass plus timber/Bamboo can be utilized in assembling sheets<sup>36</sup> and furthermore conglomerations produced using kenaf, cannabis sativa plus timber are utilized in developing inside enter-way boards and embeds for auto insides.<sup>36</sup>

### **Silk, Wool and Feathers**

Silk and wool are creature hinged strands which are utilized for assembling of pieces of clothing and have been tested as reinforcement for biocomposites. Silk is known for its solidarity, non-poisonousness, slow debasement plus biocompatibility. Prior to involving in application silk fiber should be detached by expulsion of salt gems as well as sericin coat by

bubbling silk strands in washing soft drink familiar as degumming process.<sup>55</sup>

Fleece keratin filaments are described by surface durability, giant viewpoint proportion, adaptability also slighter deliquescent than cellulose. Feather keratin filaments be bound an empty construction so that specified volume of strands holds a critical volume of air bringing about extremely low thickness approximately nearly one gram per cubic centimeter and low dielectric steady nearly 1.7 that proposes their utilization in conglomerations in galvanic functions.<sup>14</sup>

#### Others

Other used natural organic fillers can include Hair (Llama, Horse, alpaca, mohair, vicinity, cashmere, camel, rabbit); Minerals [Asbestos (rock)],<sup>46</sup> starch, palm tree flour, isora fibers, natural rubber.<sup>14, 56</sup>

#### Surface Modifications or Pretreatment Techniques

Surface change is the demonstration of adjusting the outer layer of substance through conducting compound, corporal or natural qualities not the same as the ones initially tracked down on the outer coat of stuff. Since basic expansion of normal natural fillers to a polymer<sup>1</sup> networks might prompt poor machine based belongings, so to further develop bond among supporter materials (hydrophilic) as well as polymer macromolecules (by and large hydrophobic) plus their scattering in Grid, change of filler facet is especially required..

Changes revolve around corporal plus compound methods, which can work on interfacial co-operations between supporter particles in addition to polymer lattices.<sup>1</sup>

Physical Modifications: Main techniques of physical modifications are as follows<sup>46, 57</sup>

#### Thermo Treatment

When regular strands are exposed to warm therapy exceedingly in excess of glass progress temperature of lignin then warm therapy will be helpful to adjust regular strands in conventional techniques also lignin will be mellowed and move to the strand facet as well as debases at around 214°C thus warming strand to 200°C would be supposed to give rise to a little conditioning.

#### Calendaring

It is another type of traditional surface modification method. It is a course of mellowing plus compacting stuffs in course of creation through processing a solitary ceaseless sheet using various sets of warmed rolls. The rolls in mix are familiar as calendars.

#### Discharge Treatment

Release therapy, for example, frigidness plasma, faltering plus crown release is of extraordinary attentiveness corresponding to refinement in practical belongings of regular strands. The falter drawing achieves mostly actual changes, like facet unpleasantness also this prompts attachment.

#### Surfactant Therapy

Through the covering of fillers with high sub-atomic weight polymer or low atomic weight surfactant as a rule brings about optional powers, (for example, Van der waal powers, hydrogen powers) among materials plus modifier. Principle of surfactant treatment is superior<sup>58</sup> absorption of polar groups of<sup>58</sup> surfactant (also contain long aliphatic fetters) onto giant vitality surfaces of supporters through electrostatic co-operations. Ionic bonds can likewise be shaped under specific circumstances.

#### Encapsulation

Encapsulating inorganic excellent debris with carried out polymers: In such situation, a macromolecular as well as hyper dispersant, is utilized. As like surfactant, polymeric dispersant consists of two major components (table 5.1.1.1).

#### Two Major Components of Polymeric Dispersant

Encapsulation utilizing polymers prepared through in-situ cycle which can produce extra consistent scope.<sup>57</sup>

Encapsulation through polymer coat applied on compact inorganic materials: This is accomplished through emulsion polymerization proceeding.<sup>57</sup> After polymerization, introducing initial aqua phobic coat on facet of materials<sup>59</sup> is important through pretreatment of particles with surfactants, because formation of hydrophobic layers is pivotal in production of polymer shells.<sup>57</sup>

**Table 5: The polymeric dispersant's constituents**

Component	Examples	Function
Functional groups	-NH <sub>2</sub> , -PO <sub>4</sub> <sup>2-</sup> , -OH, -COOH, -SO <sub>3</sub> H, -NR <sub>3</sub> <sup>+</sup> , -COO <sup>-</sup> , SO <sub>3</sub> <sup>-</sup>	Assists fastening dispersants to particle's surface through hydroxyl and electrostatic bonds.
Dissoluble fethers of macromolecules	Polyolefins, polyether, polyacrylate, polyester.	Suitable to be disseminate in exceptional means of stubby to excessive polarity.

### Chemical Modifications

Chemical modifications or use of adhesion promoters are capable of improving overall machine-based belongings as well as interfacial co-operations among filler particles<sup>60</sup> plus polymer matrices. Outcome of facet changes hinged on compound interactions is extra notable than physical methods for reason that there is no desorption from the particle surface due to covalent attachment modifiers. The main techniques may be summarized as <sup>1, 31, 46, 56-57, 61-67</sup>

### Oxidation Modification

Oxidation amendment can be achieved below slight conditions, in this situation -R-COOH organization, -RCHO organization and R<sub>2</sub>C=O institution may be added in cellulose fethers by using particular oxidation of Prime and subordinate -OH institution in cellulose fethers.

### Combining Negotiator Therapy

This is extremely favored plus uncomplicated applied therapy. Coupling negotiators along with SiH<sub>4</sub>, Zr<sub>2</sub>O<sub>7</sub> also TiO<sub>2</sub> are utilized to enhance adherence in middle of inorganic supporters as well as natural lattices.<sup>57</sup> Depending upon pretreatment conditions, the attached silane can lessen aqua-philic houses of SiH<sub>4</sub>. Consistent facets insurance of coupling retailers on nanoparticles is tough to comprehend by utilizing bodily and machine-based way.<sup>68</sup>

### Grafting

There may be courses commencing polymerization →first is facet changes with polymerisable classes like by silane remedy →different is floor change with commencing classes.<sup>57</sup>

### Mercerization

It is also called alkali treatment. Method normally carried out on squat strands, through warming at

approximately eighty degree celsius in ten percent of sodium hydroxide fluent mixture with reference to quarter hours, cleansing plus dehydrating in aerated microwave then permits obtaining superior strands plus enhancing strand dampening.

### Acetylation

Given technique is said to be an esterification technique which stabilizes the mobile partitions (in phrases of dampness, absorption plus spatial alteration). In this technique, firstly strands are submerged for sixty minutes in CH<sub>3</sub>COOH (glacial), and then aggregate of C<sub>4</sub>H<sub>6</sub>O<sub>3</sub> with some falls of focused H<sub>2</sub>SO<sub>4</sub>, then purified, cleansed, dehydrated in aerated oven.<sup>69</sup>

### Anhydride Treatment

Here filaments are submerged plus interact with the -OH group over filament facet, normally C<sub>4</sub>H<sub>2</sub>O<sub>3</sub> in C<sub>8</sub>H<sub>10</sub> or C<sub>7</sub>H<sup>8</sup> are utilized in given technique.

### Benzylation

This method helps in decreasing hydrophilicity of fibers. Firstly filaments are submerged in ten percent of sodium hydroxide then blended using C<sub>7</sub>H<sub>5</sub>ClO for sixty minutes, purified, cleansed, dehydrated then one more time submerged for sixty minutes in C<sub>2</sub>H<sub>5</sub>OH, washed out, dehydrated in microwave.

### TDI Treatment

TDI therapy seems to covenant finest outcomes solicitude to machine-based belongings<sup>1</sup> in which strands are submerged in CHCl<sub>3</sub> using some falls of catalysts<sup>69</sup> then toluene-2, 4-diiisocyanate is added succeeding for two hours as well as these strands are washed out in (CH<sub>3</sub>)<sub>2</sub>CO plus dehydrated in microwave.

### Plasma Therapy

This is a recent method of modifying fiber surface. Depending on treatment conditions, modifications can be very heterogeneous; therefore it is not easy to generalize.

Other methods like  $H_2O_2$  therapy, Permanganate therapy, silane therapy and  $C_2H_3NO_{45}$  can improve mechanical properties, reduce aqua-philic essence of strands also enhance interface adhesion in company of polymer grid.

### Methods of Preparation of Green Composites

The green composites can be prepared by several methods, some of these methods are discussed as<sup>44, 70-71</sup>

### Tendril Twisting

Given approach entails twisting tendrils below strain above revolving arbor (figure 6.1). Paste-permeated

uninterrupted strands get swathed on every side of revolving arbor and then resin is cured and the mandrel is removed. Basically, this approach entails following twisting designs: peripheral, polar twisting plus spiral.<sup>72</sup>

### Injection molding method (figure 6.2)

Five steps of injection molding methods

Making a mold.

- Locate framework in particular device:-the inoculation embellishment device.
- Inoculate soothed plastic substances beneath excessive stress underneath the impact of warmth within the mildew.
- Cooling the whole through cooling channels within framework.
- Vent the fraction.

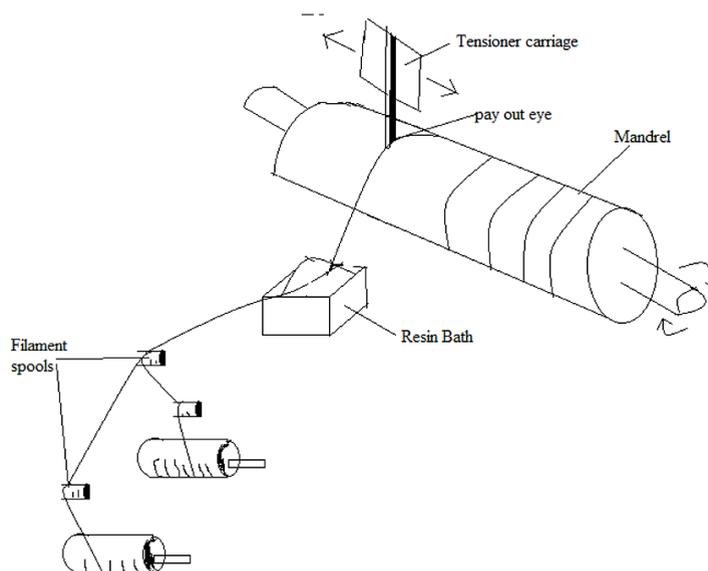


Fig. 6: Layout displaying given procedure inspired by (Jose M. Kenny, Luigi Nicolais, 1989)  
<https://www.sciencedirect.com/topics/earth-and-planetary-sciences/filament-winding>

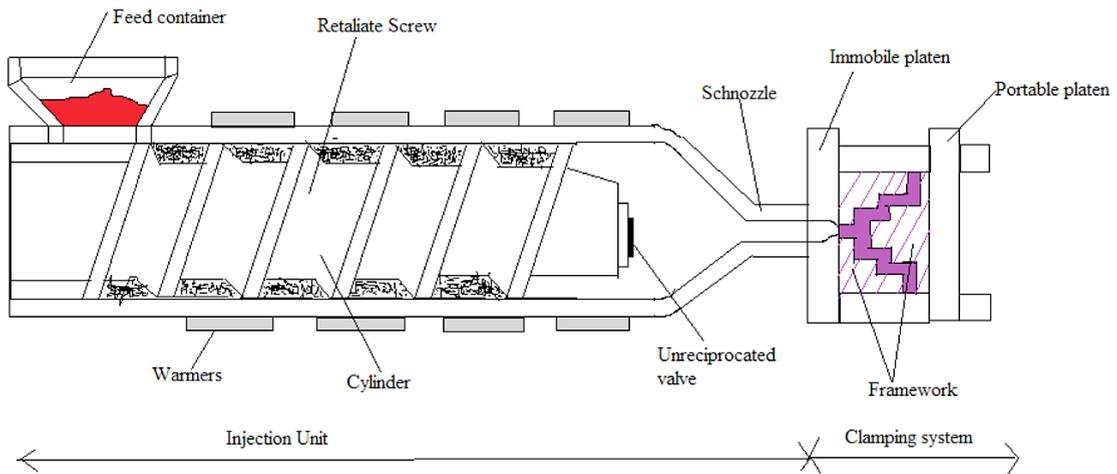
### Replicate Utilizing Next Component

Thus, there are four stages in cycle  
 Clamping → Injection → cooling → Ejection

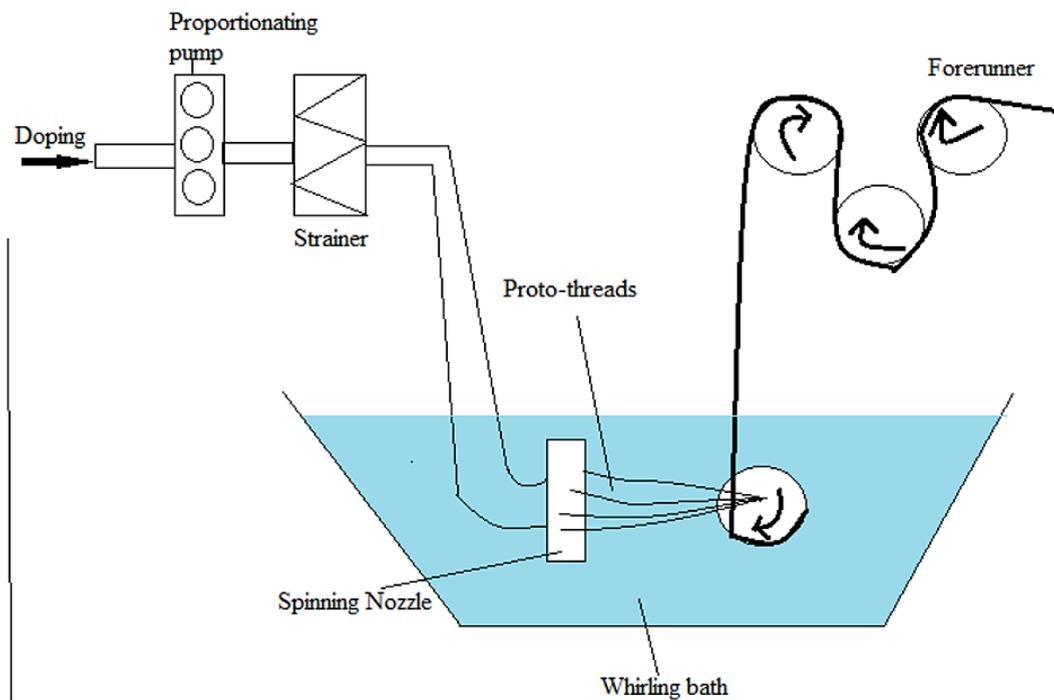
### Autoclave affixing

Autoclaves are planned to bring forth sprightly reversal for one and all fabrication load of conglomeration fraction. Fabrication process

instances are immediately dependent on the potential of the affixing autoclave to switch thermal strength into particle load. In given process, there is usage of two sided mold sets - rigid mold on decrease edge plus bendy diaphragm crafted silicone or forced out polymer along with nylon on top edge.



**Fig. 6.2 Injection molding framework inspired by**  
<https://learnmech.com/basic-injection-molding-process-diagram-working/>



**Fig. 6.4: Wet pirouette scheme<sup>73</sup>**

Sometimes, Wax film gets positioned upon squat framework plus withered augmentation is positioned above.

This manner is commonly achieved at each multiplied strain plus temperature as utilization of increased stress allows giant filament part of volume

and occasional lacuna contentment for optimum constructional performance.

**Wet Pirouette**

In this method, because mixture is squeeze out straightly through abruption liquor, therefore it is familiar as moist pirouette technique (figure 6.4). It is

used for fiber forming substance at spot of polymer flour is broken down in a reasonable dissolvable plus polymer arrangement is expelled out using threader in direction of coagulant. Filament emerges due to mutual diffusion of solvents and non solvents which precipitates from solution and solidify.

### Dry Spinning

In this process of formation of fiber, giant fume strained polymer arrangement gets exchanged in form of strong strand using superintended filament dissipation in twist line. Key factors of given strategy

may be: - mass exchange, movement of warmth plus weight on fiber as they are accomplished through dissipating dissolvable in latent gas which may be familiar as flood of air.

Hence wet spinning (figure 6.4), Dry spinning (figure 6.5) as well as liquefy plus jell pivoting are called as extrusion processes as this process is coercing stocky, gluey liquor across squat voids of apparatus said as briary for forming strings (non-stop strands) of half-stable polymer. The generic essential component of given procedure is spinneret<sup>71</sup>

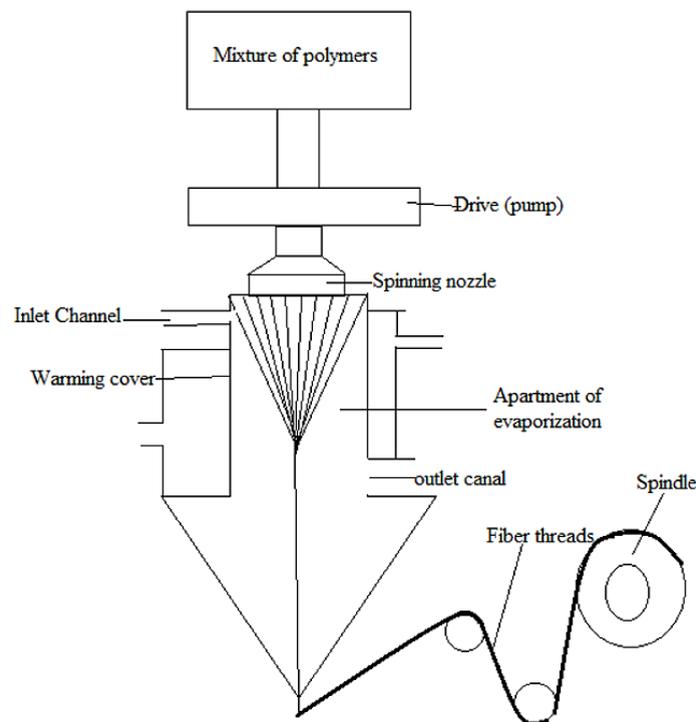


Fig. 6.5: Schematic of Dry spinning technique inspired by <https://www.dspattextile.com/2022/07/wet-melt-and-dry-jet-wet-spinning.html>

### Clip-Wings Method

Manual rest-up or proximity forming is most seasoned as well as least complex approach in preparing strand glass- pitch conglomerations. In given method, followed by giving a design of required shape, strands are sheared then escalate above template. From that point onward, when it is put in autoclave in sense of relieving beneath intensity as well as tension, vacuum sack is folded overall around spot of rest up to dispose of air, packing the part plus preparing hindrance for gathering. Solidified

fraction is taken out from shape when this fraction is relieved completely.

### Pultrusion Process

Pultrusion is a continuous process for manufacturing conglomerations having uniform fragmentary or organizational contour which shows remarkably large size. Because of its persistent, mechanized and profoundly useful nature, it is broadly utilized in composites' business. Constant meandering filaments, right off the bat, are gotten from bassinet

by way of filament pressuring gadget into sap shower, then for relieving covered filaments are gone along warmed kick the bucket plus restored fraction is then cut into wanted extent.

### Wax Exchange Forming Method

Wax exchange forming is bolted-molding fabrication technique which can be helpful in preparing glossy

facet fractions having squat coercion. Generally filaments are manually clipped into shape, afterward tar combination is immersed its hole then beneath intensity plus tension, fraction is relieved. Utilizing given technique, giant plus multiplex configurations can be made; also this process is faster than the lay-up process as low clamping pressure is required.

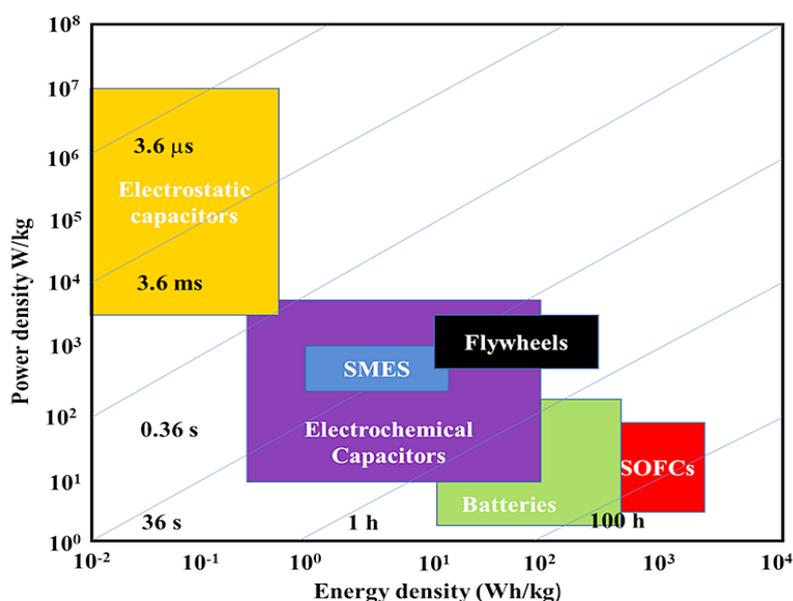


Fig. 7.1: Ragone plot of different energy storage devices

### Applications of Green Composites in Various Fields

#### Energy Storage

Research into creating dependable and eco-friendly energy storage systems has been fueled by the growing need for sustainable energy storage solutions. Batteries, solid oxide fuel cells (SOFCs), superconducting magnetic energy storage (SMES) devices,<sup>74</sup> and capacitors are some of the methods that have been studied for storing chemical, magnetic, and electrical energy (Figure 7.1). Because of their affordability, high power density, low operating voltage, and wide range of applications, capacitors are the most popular of these. They are very helpful in electronic circuits, electric cars, power grids, and renewable energy storage because of their quick cycles of charging and discharging. The efficiency and higher performance of supercapacitors, a specific type of capacitors, have drawn more and more attention.

Researchers have concentrated on eco-friendly nanomaterials and green nanocomposites to improve the sustainability of supercapacitors.<sup>75</sup> As a result, green synthesis techniques using biodegradable polymers and naturally occurring nanofillers have been developed. Enhancing electrochemical performance through the incorporation of conductive elements into polymer matrices has demonstrated significant potential. Numerous formulations of green nanocomposite materials have been investigated, incorporating metallic nanoparticles, polyaniline, and derivatives based on graphene. Increased electrical conductivity and capacitance are a result of these components' interactions, which include electrostatic and  $\pi$ - $\pi$  interactions. Notably, the addition of inorganic nanoparticles like ZnO and BaTiO<sub>3</sub>, styrene-maleic anhydride copolymers,<sup>75</sup> and graphene quantum dots has shown great promise for developing energy storage solutions.

Materials with improved structural qualities, stability, and electrical conductivity are essential for creating high-performance supercapacitors. Conducting polymers and carbon-based compounds like graphene and carbon nanotubes are essential.

### **In Biomedicine**

Effective interactions with biological materials, such as live cell tissues, are made possible by green composites having hydrophilic surfaces<sup>76</sup>. Because these materials are biocompatible and biodegradable, their bioactivity feature sets them apart from their synthetic counterparts and emphasizes their potential for use in biomedical applications. Compared to traditional materials, the use of green composites in biomedical research has several advantages. Among the main benefits are:

- Enhanced mechanical properties such as toughness and strength without increasing the overall weight.
- The ability to regulate biodegradation rates and cell permeability effectively.
- Incorporation of nutrients and growth factors to support biological processes.
- Adaptability in shaping and structuring to meet specific medical needs.

Composite-based scaffolds<sup>77</sup> have shown significant progress in tissue engineering, an interdisciplinary field that combines materials science and medical principles. The effective regeneration of articular cartilage utilizing a highly versatile three-dimensional scaffold made of poly/collagen composite, which promoted soft tissue growth, was a major breakthrough. Furthermore, by adjusting the monomer ratio, the biodegradation rate of poly(lactic-co-glycolic acid) (PLGA), a potential biomaterial, may be precisely controlled. Similarly, it has been shown that adding polyglycolic acid (PGA) to a polylactic acid (PLA) matrix<sup>78</sup> improves mechanical resilience and deterioration rates.

Bacterial cellulose from *Gluconacetobacter*<sup>79</sup> *xylinus* has advanced further and been well integrated into a PLA matrix, increasing its applicability for biomedical applications. Similarly, because of their advantageous qualities, cellulose-based composites have drawn interest. Human mesenchymal stem cells (MSCs) have been successfully seeded onto composite scaffolds<sup>80</sup> in regenerative medicine, allowing for

tissue development and cell differentiation. This method has been used to regenerate the trachea, resulting in innovative transplants that do not require immunosuppressive treatment.

Cell differentiation is significantly influenced by the stiffness and other characteristics of scaffold materials. Interestingly, green composites have bioactivity that can promote tissue growth without the need for outside growth agents. Research has shown that silk-cellulose composite scaffolds encourage MSCs<sup>81</sup> to undergo chondrogenic<sup>82</sup> differentiation, which results in the deposition of cartilage matrix *in vitro*. The amounts of functional groups like hydroxyl and amide, which have been found to be important contributors to these interactions, can be changed to maximize material performance.

Although biopolymers are already widely used in medical applications, new green composites with special functions and improved performance have recently been developed as a result of the integration of natural fibers into diverse systems. Even though this field of study is still in its infancy, ongoing developments could completely change medical care by providing ground-breaking approaches to biomaterials<sup>82</sup> engineering and regenerative medicine.

### **In Environmental Remediation**

Heavy metals such as mercury (Hg), cadmium (Cd), lead (Pb), and arsenic (As) are among the most hazardous pollutants in the environment. While some metals like iron ( $\text{Fe}^{2+}$ ) are essential for biological functions, their oxidized forms, such as  $\text{Fe}^{3+}$ , can be toxic. Similarly, copper ( $\text{Cu}^{2+}$ ) is necessary for physiological processes, but excessive levels can cause severe damage to the liver and kidneys.

To mitigate the toxic effects of heavy metals, eco-friendly methodologies have gained attention, particularly in the development of nanomaterials for efficient metal detection.<sup>83</sup> Carbon dots synthesized from flour have shown remarkable selectivity for detecting mercury ions at ultra-low concentrations.<sup>84</sup> Similarly, gold nanoparticles (AuNPs) derived from *Hibiscus cannabinus* leaf extract have exhibited high specificity toward  $\text{Fe}^{3+}$  ions, with notable sensitivity in detecting trace levels. Another promising approach involves the use of *Trichoderma harzianum*-capped

AuNPs for mercury detection in water, utilizing colorimetric changes as an indicator.

Nanoparticles derived from naturally occurring compounds such as glutathione have also demonstrated significant potential in sensing mercury ions, while graphene quantum dots (GQDs) stabilized with L-ascorbic acid have been effective in detecting lead ions at nanomolar concentrations. Silver nanoparticles (AgNPs) synthesized using *Hibiscus sabdariffa* leaf extract have shown the capability to detect multiple heavy metals, including cadmium, lead, and mercury. Similarly, silver-graphene oxide composites prepared with ascorbic acid and beta-cyclodextrin have been employed for arsenic detection in water samples.

Other notable green approaches include bio-functionalized AgNPs from *Polyalthia longifolia* leaves for mercury detection and fluorescent carbon

nanoparticles synthesized from D-glucose for iron sensing. Additionally, nitrogen-doped carbon dots produced from *Prunus avium* fruit extract and carbon dots from rose heart radish have displayed exceptional sensitivity for Fe<sup>3+</sup> ion detection. Lead sulfide nanoparticles (PbS NPs) obtained from endophytic fungi have also been utilized for arsenic sensing at trace levels. Table 7.3 displayed below summarize green synthesized nanomaterials for detecting heavy metals<sup>85</sup>:

Among various nanomaterials, gold and silver-based nanoparticles remain prominent due to their strong affinity for metal ions, making them highly effective in environmental monitoring. Fluorescent sensors, particularly those based on carbon nanostructures, have emerged as promising candidates for the rapid detection of toxic metals, ensuring precise and reliable assessments in contaminated environments.

**Table 7.3: Eco-friendly nanomaterials for heavy metal sensing**

Green-derived nanomaterial	Particle size (nm)	Detection Threshold (LOD)	Target Metal Ion(s)	References
Carbon dots obtained from flour	1-4	0.5 nM	Hg <sup>2+</sup>	86
Gold nanoparticles synthesized using <i>Hibiscus cannabinus</i> extract	22	0.0037 μM	Fe <sup>3+</sup>	87
<i>T. harzianum</i> -functionalized gold nanoparticles	30	2.6 nM	Hg <sup>2+</sup>	88
Carbon nanoparticles infused with glutathione	2.93	0.05 nM	Hg <sup>2+</sup>	89
Graphene quantum dots (GQDs) prepared with L-ascorbic acid and polystyrene sulfonate	5-15	7 x 10 <sup>-9</sup> M	Pb <sup>2+</sup>	90
Silver nanoparticles from <i>Hibiscus sabdariffa</i> extract	5-30	-	Hg <sup>2+</sup> , Pb <sup>2+</sup> , Cd <sup>2+</sup>	91
Silver-graphene oxide hybrid derived from ascorbic acid and beta-cyclodextrin	10-60	0.24 nM	As <sup>3+</sup>	92
<i>Polyalthia longifolia</i> -derived silver nanoparticles	5	-	Hg <sup>2+</sup>	93
Fluorescent carbon nanoparticles synthesized from D-glucose	5	18 ppm/ 56.0 ppb	Fe <sup>3+</sup>	94
Nitrogen-doped carbon dots extracted from <i>Prunus avium</i> fruit	5	0.96 μM	Fe <sup>3+</sup>	95
Carbon dots obtained from rose heart radish	1.2-0.6	0.02-40 μM	Fe <sup>3+</sup>	96
Lead sulfide (PbS) nanoparticles derived from endophytic fungi	35-100	50 ppb	As <sup>3+</sup>	97
Silver nanoparticles synthesized from <i>Matricaria recutita</i> extract	11	-	Hg <sup>2+</sup>	98
Silver nanoparticles stabilized using carboxymethyl gum karaya	12.1	10 nM	Cu <sup>2+</sup>	99

### In Functional Coatings

Green composites, which are made from bio-based or biodegradable materials, have attracted a lot of interest in functional coatings<sup>100</sup> because of their higher performance qualities, sustainability, and environmental friendliness. These coatings have improved qualities like durability, corrosion resistance, antibacterial activity, and self-repairing capabilities<sup>101</sup> because they contain natural fibers, bio-polymers, and specialty additives. Their use helps to lessen the environmental impact while also reducing dependency on coatings derived from petroleum.

Natural fibers, eco-friendly crosslinkers, and bio-based polymers are the main ingredients of green composite coatings. The main matrix is made up of natural polymers such as cellulose, chitosan, polylactic acid (PLA),<sup>102</sup> and soy protein, which provide sustainability and biodegradability while maintaining superior functional qualities. The mechanical strength, adhesion, and barrier effectiveness of the coatings are improved by reinforcement materials such as lignocellulosic fibers (such as flax, hemp, and kenaf)<sup>103</sup> and fillers like nanocellulose and montmorillonite (MMT).<sup>104</sup> Furthermore, performance is enhanced without sacrificing environmental safety through the use of plant-derived antioxidants, antibacterial agents, and environmentally friendly crosslinkers including genipin and tannins.

Numerous functional characteristics of these green composite coatings make them extremely advantageous in a range of applications. Because of their superior barrier qualities, which offer robust defense against moisture, oxygen, and chemical deterioration, they are perfect for food packaging and corrosion prevention. Antimicrobial compounds like chitosan, silver nanoparticles, or aromatic oils can be added to coated surfaces to assist stop microbial infection.<sup>105</sup> Self-healing mechanisms are another property of some bio-based coatings that enable them to fix small damage, extending their lifespan and lowering maintenance requirements.<sup>106</sup> Furthermore, lignin or natural antioxidants improve thermal and UV stability, which increases the coatings' longevity.

Green composite coatings are widely used in a variety of industries because of their adaptable qualities. They offer lightweight, corrosion-resistant

protective coatings for automobile and aircraft body parts in the automotive and aerospace industries.<sup>107</sup> These coatings are utilized in the biomedical industry for implants, wound dressings, and medical devices where antimicrobial protection<sup>105</sup> is essential. Their high-barrier and sustainable coatings for food and pharmaceutical packaging serve the packaging sector by guaranteeing product safety and longer shelf life. These environmentally friendly coatings are also used by the marine and construction sectors to safeguard infrastructure, such as ships, bridges, and buildings, in order to reduce their negative effects on the environment.

Green composite coatings provide substantial benefits in terms of environmental responsibility and functional performance as sustainable substitutes for traditional synthetic coatings. They are a potential alternative for a greener future if ongoing research and development in this area can enhance their qualities, broaden their uses, and enable large-scale commercialization.

### In Electronics and Sensors

Because of their environmentally benign and sustainable methods of producing electronic devices, green composite-based electronics and sensors are becoming more and more popular. These composites provide structural integrity while reducing their negative effects on the environment by using biodegradable polymers as the matrix, such as cellulose, chitosan, polylactic acid (PLA),<sup>14, 102</sup> and starch. The electrical, mechanical, and functional qualities of these materials are improved by reinforcing agents such as carbon nanotubes (CNTs), graphene, lignocellulosic fibers, and nanocellulose. Furthermore, sensor performance can be further enhanced without the use of dangerous elements by including non-toxic conductive fillers such as polyaniline, silver nanowires, and bio-derived carbon compounds.<sup>108</sup> This combination of materials enables the development of high-performance, biodegradable electronics and sensors that contribute to the reduction of electronic waste.

The versatility of green composite-based electronics in a range of technical applications is one of its main benefits. They are perfect for creating biodegradable flexible circuits, wearable health monitoring gadgets, and sustainable energy storage solutions since they

can reliably conduct electricity through bio-based and non-toxic conductive additives.<sup>109</sup> Additionally, these composites facilitate the creation of stretchy electronics, which are essential for use in skin-interfaced biosensors, smart textiles, and human motion sensing. Green composites also aid in the creation of self-powered sensors that use triboelectric or piezoelectric principles,<sup>110</sup> providing an energy-efficient method of monitoring the environment and human health in real time.

In addition to their electrical characteristics, green composites have outstanding chemical stability and adjustable rates of degradation, which may be managed by altering the filler content, crosslinking density, and polymer composition. This is especially helpful in biological applications that need biodegradable biosensors and temporary electronic implants. Green composite-based sensors offer a novel method for real-time pollutant detection in environmental applications. They can detect organic pollutants, heavy metals, and microplastics

in water and air.<sup>111</sup> Furthermore, developments in additive manufacturing (3D printing) have made it possible to precisely fabricate electrical components made of green composites, enabling rapid prototyping of biodegradable sensor arrays and energy storage devices as well as customizable designs.

High-performance and more environmentally friendly electronic devices are being made possible by developments in green composite-based electronics and sensors. Key developments including self-powered electronics, biodegradable components enabled by 3D printing, and the integration of green composite sensors with IoT and AI for real-time monitoring are highlighted by a number of emerging trends and future directions, which are compiled in Table 7.5. It is anticipated that these advancements would greatly improve the scalability, robustness, and functionality of environmentally friendly electronic systems.

**Table 7.5: Emerging Trends and Future Directions in Green Composite-Based Electronics and Sensors**

Aspect	Description
Self-powered electronics	Integration of piezoelectric and triboelectric nanogenerators to create energy-efficient sensors.
3D printing and additive manufacturing	Enables precise fabrication of biodegradable electronic components, allowing for customized designs and scalability.
Smart and responsive materials	Development of composites with stimuli-responsive properties (e.g., shape memory, color change upon exposure to contaminants).
Integration with IoT and AI	Green composite sensors can be connected to IoT networks and AI-based data processing for advanced real-time monitoring.
Hybrid bio-based conductive materials	Research into combining bio-derived carbon with metal-organic frameworks (MOFs) for enhanced conductivity and selectivity.
Edible and transient electronics	Exploration of fully degradable and even edible electronic components for food safety monitoring and medical diagnostics.
Sustainable Energy storage	Use of bio-derived electrodes for green supercapacitors and batteries, enabling eco-friendly power solutions.

### Critical Analysis

Some general observations and insights based on citations provided in this review article:

Green composites could offer several benefits compared to traditional composites made from synthetic fibers and petroleum based polymers but

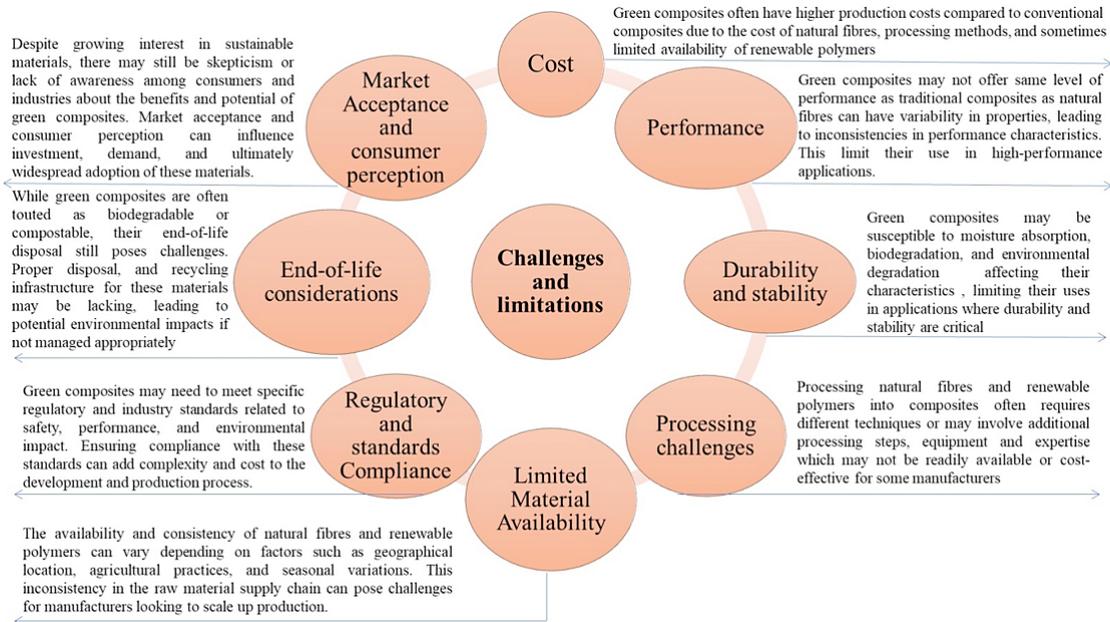
their widespread adoption may still faces challenges and limitations (figure 8.1). They may be:

Addressing these challenges requires continued research and development efforts to improve the performance, durability, and cost-effectiveness of green composites, as well as investment in

infrastructure and standards to support their widespread adoption across various industries.

Certainly, green composites which are composed of natural fibres such as jute, hemp flax, or kenaf, embedded in a biopolymer matrix, offer several advantages over traditional composites, which are

typically made from synthetic fibres like carbon or glass embedded in a polymer matrix. Despite facing challenges, the performance of green composites can indeed surpass traditional counterparts in certain aspects, and they also exhibit economic feasibility for large-scale production.



**Fig. 8.1: Challenges in path of widespread adoption of green composites**

Here are some reasons why green composites excel in certain areas:

**Environmental Sustainability**

Green composites are derived from renewable resources, making them more environmentally friendly compared to composites based on synthetic fibres. The use of natural fibre reduces the dependency on non-renewable resources and lowers the carbon footprint associated with composite production.

**Weight Reduction**

Natural fibres are typically lighter than synthetic fibres, leading to reduced overall weight in composite structures. This advantage is especially crucial in applications where weight reduction is essential, such as automotive and aerospace industries, as it contributes to improved fuel efficiency and enhanced performance.

**Improved Specific Properties**

Green composites can exhibit specific properties such as high specific strength and stiffness, as well as good impact resistance, which can be comparable to or even better than those of traditional composites. This is particularly true for certain natural fibres like flax or jute, which possesses inherent mechanical properties suitable for various applications.

**Reduced Processing Costs**

In some cases, the processing of green composites can be less energy-intensive and require lower processing temperatures compared to traditional composites, resulting in reduced production costs. Additionally, natural fibres are often cheaper than synthetic fibres, contributing to cost savings in material procurement.

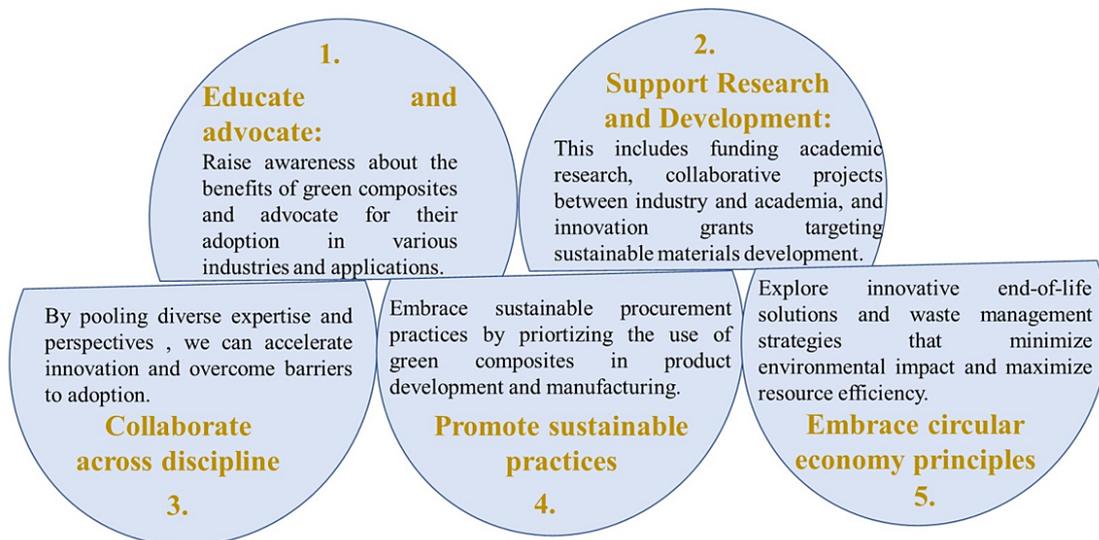
**Waste Management Benefits**

The use of natural fibres in green composites can offer benefits in terms of waste management. Agricultural residues or by-products can be utilized as feedstock for natural fibres, providing an opportunity for waste valorization and contributing to the circular economy approach.

However, despite these advantages, widespread adoption of green composites faces challenges, to overcome these challenges and fully realize the potential of green composites, on-going research and development efforts can be focused on improving fibre quality and consistency, optimizing processing techniques, enhancing compatibility between fibres and matrices, and exploring novel reinforcement

strategies. Additionally, continued advancements in recycling and end-of-life management of green composites will further strengthen their economic feasibility and environmental sustainability.

As researcher, it's essential for us to recognize the transformative potential of green composites in fostering sustainability and environmental stewardship. This review on green composites offers valuable insights into the innovative materials and processes driving this paradigm shift towards a greener future. However, to truly harness the benefits of green composites and propel their widespread adoption, collective action is imperative. Here are some steps (figure 7.2) that we can take:



**Fig. 8.2: Imperative collective actions**

By taking proactive steps and embracing a collective commitment to sustainability, we can play a pivotal role in realizing the transformative potential of green composites and shaping a more environmentally conscious future. Together, we can contribute to building a world where innovation and sustainability go hand in hand, fostering a harmonious relationship between human activities and the natural environment.

**Conclusion**

This paper has explored the growing importance of green composites, especially due to the reduction

in the use of petroleum-based, non-renewable resources and the increased use of ecological assets. A key advantage of green composites is their lower cost of raw materials, which makes them a viable alternative to traditional composites. The selection of natural fibers and appropriate matrix systems is critical, as it directly influences the final properties of the composites. Statistical analysis, stiffness, and strength values are essential factors in determining the best combination of fibers and matrices.

Various polymer matrices, including polyethylene, polypropylene, polyesters, epoxy, phenolic resin, PLA, PHA, and PCL, have been examined, along with natural organic fillers such as sisal, jute, hemp, rice husk, corn husk, silk, and wool. These materials offer a wide range of possibilities for green composite development. Additionally, surface modification methods have been discussed as essential for enhancing the adhesion between the polymer matrix and natural fillers, thereby improving the overall performance of the composite.

The main results indicate that green composites hold significant promise in industries such as automotive, construction, and packaging, where sustainability, cost-effectiveness, and performance are highly valued. The ongoing research into bio-derived polymers and surface modification techniques will further enhance the properties of these materials, expanding their applications. Therefore, green composites are positioned to play a key role in the transition to more sustainable material solutions in various sectors.

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#### Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data Availability statement

This statement does not apply to this article.

#### Ethics Statement

This review did not involve human participants, animal subjects, or any material that requires ethical approval.

#### Informed Consent statement

This study did not involve human participants and therefore informed consent was not required.

#### Clinical Trial Registration

If statement is not there mention this statement.

#### Permission to Reproduce Material from other Sources

Not Applicable.

#### Author Contributions

- **Nibedita Banik:** conceptualized the study, supervised the research work, and provided critical revisions to enhance the manuscript.
- **Navdeep Kaur:** conducted the literature review, drafted the manuscript, and contributed to data analysis and interpretation. Both authors discussed the results, reviewed the final manuscript, and approved it for submission.

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