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Polyvinyl Chloride (PVC)-Based Biocomposites and Bionanocomposites: State-of-the-Art, New Challenges, and Opportunities

Shiv Kumari Panda[1]*, Visakh P. M[2] and Nadir Ayrilmis[3]

[1]*Department of Chemistry, U.N. Autonomous College of Science & Technology, Adaspur, Cuttack, Odisha, India*
[2]*Natural Bioactive Materials Laboratory, Department of Bioengineering, Ege University, Bornova/Izmir, Turkey*
[3]*Department of Wood Mechanics and Technology, Faculty of Forestry, Istanbul University – Cerrahpasa Bahcekoy, Sariyer, Istanbul, Turkey*

Abstract
This chapter provides a short version of all the other chapters. Here we write about the different chapter topics such as polyvinyl chloride/starch-based biocomposites and bionanocomposites; polyvinyl chloride/polylactic acid-based biocomposites and bionanocomposites; flame retardancy of polyvinyl chloride (PVC)-based biocomposites and bionanocomposites; interfacial modification of polyvinyl chloride (PVC)-based biocomposites and bionanocomposites; sustainable PVC biocomposites and bionanocomposites: a path towards green innovation; polyvinyl chloride (PVC)/cellulose-based biocomposites and bionanocomposites; biodegradation of polyvinyl chloride (PVC)-based different fibers bionanocomposites; polyvinyl chloride (PVC)-based biocomposites and bionanocomposites for biomedical applications; polyvinyl chloride (PVC)-based hybrid biocomposites and bionanocomposites; and preparation and PVC/rubber bio nano blends.

***Keywords*:** Polyvinyl chloride, biocomposites, starch, rubber, nano blends, biomedical and bionanocomposites

**Corresponding author*: shivkumaripanda@gmail.com

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1.1 Polyvinyl Chloride (PVC)/Starch-Based Biocomposites and Bionanocomposites

Starch is one of the most abundant naturally occurring polysaccharides that can be obtained from natural sources like corn, potato, and cassava. It is a renewable, nontoxic, economical, and biodegradable polymer that is second to cellulose in occurrence. It is extensively available in the seeds, roots, and leaves of varieties of plants, and some algae. Starch-based biocomposites and bionanocomposites have been studied widely for their easy availability, inexpensiveness, ease of processibility, and various chemical and physical properties [1, 2]. Starch is a primary energy source. Plants like potato, corn, cassava, wheat, millet, rice, corn, barley, sago, peas, mung beans, arrowroot, banana, yam, sorghum, lentils, and many others are utilized to obtain starch [3–5], which is stored in various parts, including the roots, seeds, tubers, and stems [6]. The nanostarches are of two different types: starch nanocrystals (SNCs) and starch nanoparticles (SNPs). SNCs are crystal-like portions that can result from the disruption of amorphous areas in starch granules, whereas SNPs are produced from amorphous regions of gelatinized starch [7, 8].

Polyvinyl chloride (PVC) is a widely used synthetic thermoplastic polymeric material known for its affordability with various types of characteristics like outstanding insulating capabilities, ease of use, fire resistance, and resistance to chemicals [9, 10]. Also, it has a great utilization in construction [120], electronics [11], automotive [12, 13], packaging [14, 15], and healthcare [16]. But the problem is that it remains chemically and physically inert for many years even after proper disposal due to the evil effect of chlorine, which is the main culprit for environmental pollution. So biodegradable fillers like starch were introduced to produce biocomposites from petroleum-based polymer resins like PVC. According to earlier studies, there are various techniques used for the synthesis of biocomposites through coprecipitation of cross-linked starch xanthate with a PVC latex and dry mixing of starch and PVC and co-concentration of starch and PVC latex [17]. If we consider the characterization of the biocomposite here, then some mechanical studies presented the reduction in tensile strength and elongation at break due to the introduction of starch in PVC [18]. Incorporating nanostarch with PVC can improve the overall biodegradability of the resulting bionanocomposite. In addition to that, samples with higher starch content showed negligible weight loss after prolonged exposure to simulated soil that is due to the encapsulation of starch by the PVC polymer matrix that can hinder the microbial degradation.

PVC is the plastic phase, and starch is the rubbery phase, and due to the combination, the amorphous parts of starch undergo a transition from glassy to rubbery state. Again, thermogravimetric analysis (TGA) indicated that overall maximum degradation value of PVC gets positively influenced by the incorporation of starch. In addition to it, another important conclusion has been made from a study that more concentration of starch can enhance the degree of dechlorination.

1.2 PVC/PLA Composites/Biocomposites

PLA is melt-blended with other elastomeric polymers such as poly(e-caprolactone), poly(butylene succinate), poly(hydroxyl butyrate), and poly butylene adipate-co-terephthalate. PLA is also melt blended with non-biodegradable polymers including polypropylene (PP), polyacrylonitrile (ABS), polystyrene (PS), polyethylene (PET), polymethyl methacrylate (PMMA), polyvinyl alcohol (PVA), polyethylene (PET), polyvinyl chloride (PVC), etc. [19]. PVC goods are widely used because of their low cost and high performance, making it a desirable material for practical applications [20]. This has contributed to the widespread usage of PVC but also has resulted in concern for its non-biodegradable nature. However, PVC/PLA blends can be tailored to have desirable features of both the components in pursuit of sustainable practices [21]. The polycondensation of the two enantiomers of lactic acid leads to the formation of three different forms of PLA: poly(L-lactic acid) (PLLA), poly(D,L-lactic acid) (PDLLA), and poly(D-lactic acid) (PDLA). The crystalline structure of PLLA-α form has been confirmed by employing neutron diffraction and two-dimensional wide-angle X-ray techniques [22]. PLLA exhibits a comparatively elevated melting temperature (T_m). PDLA is classified as a semi-crystalline polymer, whereas PDLLA is categorized as an amorphous polymer. PDLLA is a racemic polymer with an unsystematic sequence of the enantiomers. Several factors, such as the polymer's molecular weight, temperature, processing time, and duration of annealing treatment, can impact the degree of crystallinity [23]. PLA is a polymer derived from sustainable sources and is completely capable of undergoing biodegradation, making it environmentally friendly. Typically, PLA is sourced from plant-based materials like corn, wheat, or rice. PLA requires much less energy to produce compared to petroleum-based polymers. Estimations indicate that in the future, this energy need can be further lowered to less than 10%. Reducing energy consumption also has the potential to make PLA production more cost-effective [24]. Polyvinyl chloride, also known as PVC, is a linear thermoplastic polymer. Typically, PVC has a low number of branches per molecule, usually less than 10. It is unlikely for there to be multiple long chains within a single molecule. When a chlorine atom is present, it enhances the attraction between molecules and contributes to the hardness and stiffness of the polymer [25]. Polyvinyl chloride (PVC) is considered one of the most efficient petroleum-based thermoplastic polymers. It holds a significant share among the six commonly used commercial polymers and is projected to experience a steady growth rate in the coming years. The global production capacity of PVC has reached millions of tons, which is used in a wide range of applications. Sadly, they often wind up in trash heaps after being used as lightweight, single-use products like cooking oil and fruit juice packaging, and they can create major environmental damage when not disposed of appropriately [26].

PVC/PLA blend is a highly promising biodegradable polymer blend that has garnered significant attention from researchers in recent times. Literature reports the development and characterization of novel biomaterials (bioblends) made from poly(vinyl chloride) (PVC) and poly(lactic acid) (PLA) [27]. Hachemi, Belhaneche-Bensemra, and Massardier used melt mixing to obtain PVC/PLA bioblends with and without the addition of MAH as a compatibilizer. Dicumyl peroxide (DCP) was used as an initiator during *in situ* compatibilization with MAH. The incorporation of MAH improved the processability of the bioblends by reducing the mixing temperature [28]. Polymethyl methacrylate (PMMA) was utilized by Singh *et al.* as a compatibilizer to enhance the interfacial activity of PVC/PLA blends to further obtain a biodegradable film. A condensation method was used to synthesize PLA while solution casting technique was used to develop PVC/PLA blend films with and without the addition of PMMA as a compatibilizer [29]. A torque rheometer is generally utilized to melt-mix of PVC/ PLA in addition to employing various analytical techniques to study the phase morphology and compatibility of the blends. Generally, the compatibility of the two polymers is determined by studying the steady-state and dynamic rheological responses [30]. Systematic evaluation of the PVC/PLA blends' static and dynamic rheological properties offers valuable insights into their compatibility. The rheological analyses reveal important information regarding the viscoelastic behavior, melt viscosity, and other rheological properties of the polymer blends [31]. Santana *et al.* examined the biodegradation of PVC/PLA blend under soil burial (up to 180 days) through the use of a range of analytical techniques, including FTIR, TGA, and SEM, to closely monitor the physical and chemical changes occurring in the PLA/PVC blend during the biodegradation process. The degree of biodegradation was evaluated through measurements of mass loss, changes in mechanical properties, and the identification of specific functional group alterations. There were distinct changes in the chemical structure of the blend, indicating the gradual decomposition of the PLA portion. The mechanical properties of the blend, such as tensile strength and elongation at break, decreased over the burial period, further corroborating the ongoing biodegradation process [32].

1.3 Flame Retardancy of Polyvinyl Chloride (PVC)-Based Biocomposites and Bionanocomposites

The most commonly used plastics in manufacturing WPCs are polyethylene (PE) [33, 34], polypropylene (PP) [35, 36], polystyrene (PS) [37], and polyvinylchloride (PVC) [38]. The synergistic effect of ZnO and FRW on veneered WF-PVC also exhibited excellent flame retardancy [39]. The zinc borate was added to WF-PVC composite; the results showed that zinc borate had some flame retardancy on the composite, especially exhibiting an excellent smoke suppression effect [40]. The flame-retardant mechanism of zinc salts in PVC is mainly the Lewis acid catalytic mechanism in condensed phase [41], that is, zinc compounds react with HCl which is removed from PVC to give $ZnCl_2$. In the research of PVC flame retardant and smoke suppression theory, people mainly try to reveal its flame retardant and smoke suppression mechanism by studying the changes in pyrolysis products. Iida [42] studied the changes and pyrolysis mechanism of aromatic compounds in PVC pyrolysis products using Py GC.

Research has found that SnO_2 and ZnO affect the pyrolysis pathway of PVC, leading to the formation of products that favor aliphatic compounds. The production of benzene and its aromatic compounds decreases, while the effects of TiO_2 and Al_2O_3 are not significant. Montaudo [43] found that the pyrolysis process of PVC is divided into two stages, and different stages generate two different types of aromatic compounds: substituted aromatic compounds and condensed aromatic compounds. In the presence of ZnO, there is a significant difference in the generation rate of these two types of aromatic compounds. The addition of ZnO and Fe_2O_3 advances the temperature corresponding to the maximum thermal weight loss in the first stage of WF-PVC material and significantly increases the peak thermal weight loss rate. The peak mass loss rate of WF-PVC material in the first stage is 8.4, while the peak mass loss rate of zinc oxide composite material reaches 21.3, and the peak mass loss rate of Fe_2O_3 composite material is 13.6. Li Bin [44] found that CuO promotes cross-linking reaction in the early stage of PVC, reduces the amount of volatile pyrolysis products, and promotes carbonization more effectively than Fe_2O_3 in PVC when studying the pyrolysis effect of CuO, Fe_2O_3, and MoO_3 on hard PVC. Pihong [45] also studied the effect of ZnO, CuO, and Fe_2O_3 on the changes in the condensed structure and found that CuO had the best effect on promoting the carbon chain of PVC to crosslink structure and improving the gel content, while ZnO had the worst performance. The loss modulus gradually increases from WF/PVC to WF/PVCMZ-6, which is attributed to the MMT@ZnO possibly hindering the movement of PVC molecular chains and requiring more energy during relaxation [46]. The glass transition temperature (Tg) can be regarded as the damping temperature [41]. After adding MMT@ZnO nanosheet, the Tg is prolonged to a relatively higher value due to the strong interaction between MMT@ZnO and WF/PVC.

1.4 Interfacial Modification of Polyvinyl Chloride (PVC)-Based Biocomposites and Bionanocomposites

Modifying PVC with various fillers is crucial for tailoring its properties to meet a wide range of application needs [47]. Mechanical reinforcements using fibers, both natural and synthetic, are commonly employed in polymer composites. While traditional synthetic fibers like aramid, carbon, and glass have been widely used, environmental concerns have driven the shift toward more sustainable natural fibers. Synthetic fibers are known for their superior mechanical properties and thermal stability. Thermal modifiers like organotin, calcium-zinc, and magnesium hydroxide are essential for improving PVC's thermal stability and fire resistance, which are critical for safety in electrical installations and building materials [48–50]. Electrical and magnetic enhancers, including conductive elements like carbon nanotubes, graphene, and various metal nanoparticles, significantly boost PVC's electrical and magnetic properties, making it ideal for advanced electronic applications and effective as shielding materials [51–56]. A variety of fillers have been incorporated into PVC composites to enhance mechanical and thermal properties; extensive research continues to explore the potential of biomaterials in developing high-performance engineering products. Biocomposites, which are not only cost-effective and biodegradable but also characterized by their low density and availability, offer significant adaptability for various applications [57–60]. Augier *et al.* demonstrated that PVC–vegetable fiber composites not only improve the stability and mechanical properties of PVC but also allow the composite to be recycled up to five times without substantial degradation in performance [61]. This recycling capability highlights the potential for internal waste to be effectively reused within the production cycle, reinforcing the sustainability of the composite from an industrial perspective. PVC/rice straw composites have been studied extensively to assess the effects of various factors such as pretreatment, PVC content, and temperature on their properties [81]. Results show that rice straw treated with 5% and 10% NaOH at 80°C resulted in composites with higher tensile strength, while those treated with water at 130°C exhibited the lowest strength, the effect of treatment on the swellability percentage, highlighting the effectiveness of alkali treatment in enhancing the water resistance of PVC composites compared to the untreated control.

In PVC–rice husk biocomposites, epoxidized natural rubber (ENR) has been employed as a plasticizer and a compatibilizer, demonstrating considerable miscibility with PVC and enhancing its mechanical properties due to the polar nature of both polymers [62]. The study further explores the effects of rice husk content, particle size, and ENR content, identifying an optimal formulation of 90:10:20 wt.% for PVC:ENR:rice husk, which results in superior composite properties. The resulting PVC–OHF biocomposites demonstrated substantially improved thermal and mechanical stability with varied OHF content ratios. Composites using chemically treated OHF showed enhanced tensile strength compared to those with untreated OHF, which suffered from poor dispersion and agglomeration, leading to non-uniform stress and reduced binding forces within the composite [63]. Furthermore, the mechanical, thermal, and morphological properties of PVC–Alfa composites have shown remarkable improvement in thermal stability with the addition of maleic anhydride grafted PVC, illustrating the significant role of compatibilizers in enhancing composite performance [64]. Integrating these nanomaterials into PVC biocomposites has shown substantial enhancements across a wide range of properties; effective dispersion and optimal particle size are crucial for maximizing the performance for various applications [65–67]. Nanomaterials in these composites, characterized by their high surface area-to-volume ratio and surface functionality (especially the abundance of –OH groups), tend to aggregate, which can negatively affect properties. To counter this, surface modification of nanoparticles is essential to block these functionalities, prevent aggregation, and ensure uniform dispersion. Building on this knowledge, further reinforcement of PVC nanocomposite films with ZnO nanoparticles, modified by CA and vitamin C, was found to substantially increase flame retardancy [68]. Moreover, the mechanical properties, especially elongation at maximum stress, were markedly improved. These findings emphasize the effectiveness of ZnO as an additive in enhancing both the safety and durability of PVC-based materials. The mechanical parameters, such as tensile strength, Young's modulus, and elongation at maximum stress, were measured and compared between PVC and PVC/ZnO–chitosan composites. The results showed significant improvements in tensile strength, Young's modulus, or the composite films compared to neat PVC. This enhancement is largely due to the presence of chitosan and its strong bonding with both ZnO and PVC.

1.5 PVC–Nanocellulose Biocomposites and Nanocomposites

Nanocellulose, a bio-derived nanomaterial extracted from cellulose-rich sources like wood pulp, agricultural residues, and microbial cultures, has garnered considerable attention for its exceptional mechanical properties, high aspect ratio, large specific surface area, and modifiable surface chemistry [69, 70]. Its three primary forms, cellulose nanofibrils (CNFs), cellulose nanocrystals (CNCs), and bacterial nanocellulose (BNC), differ in crystallinity, morphology, and processing routes [71, 72]. CNCs, characterized by high crystallinity, are typically produced *via* acid hydrolysis, while CNFs are obtained through high-shear mechanical techniques. PVC–nanocellulose composites leverage the synergistic integration of a widely used thermoplastic polymer with a sustainable, high-performance nanofiller [73]. Incorporating CNCs or CNFs into PVC matrices results in substantial improvements in mechanical behavior (e.g., tensile strength, Young's modulus), primarily due to the high aspect ratio and interfacial bonding capacity of nanocellulose. Despite PVC's inherent non-biodegradability, nanocellulose additions reduce the overall environmental impact of the composite, offering partial biodegradability and enhanced recyclability. Nevertheless, end-of-life disposal concerns persist due to potential toxic emissions associated with PVC degradation [74]. Nanocellulose is sourced from wood pulp, agricultural residues, and bacterial fermentation, with each source influencing its properties and effectiveness. Wood pulp, a traditional source, is processed mechanically or chemically to break down fibers into nanoscale dimensions, yielding high crystallinity and mechanical strength suitable for paper and packaging [69]. Agricultural residues, such as wheat straw and rice husks, provide an eco-friendly alternative, reducing dependence on forest resources while aiding in waste management. These residues offer unique properties due to their lignin and hemicellulose content, which affect their mechanical and thermal behavior [75]. Cellulose nanofibers (CNFs), recognized for their unique properties, are composed of elongated, flexible fibers that encompass both crystalline and amorphous regions. These fibers are produced *via* high-pressure homogenization or grinding techniques, resulting in a high aspect ratio and exceptional flexibility, which render them ideal for reinforcing various materials. Additionally, CNFs demonstrate biocompatibility, biodegradability, and an extensive surface area, thereby enhancing their interactions with other substances.

In composites, it enhances mechanical properties and thermal stability, supporting applications in packaging, automotive, and construction [76, 77]. Advanced analytical tools, such as atomic force microscopy (AFM), X-ray diffraction (XRD), and dynamic light scattering (DLS), are used to study nanocellulose morphology and crystallinity. Its shear-thinning rheological behavior is beneficial for food and pharmaceutical applications [78, 79]. Polyvinyl chloride (PVC) is a high-strength thermoplastic polymer known for its durability and versatility. It is synthesized through the polymerization of vinyl chloride monomers derived from petroleum or natural gas [20, 80]. The molecular structure of polyvinyl chloride (PVC) is defined by a two-carbon backbone, in which one hydrogen atom is substituted by a chlorine atom, resulting in the chemical formula $(C_2H_3Cl)_n$. The incorporation of fillers such as clay, wood flour, and plant-based materials significantly improves its mechanical and thermal performance, thereby expanding its applicability in advanced engineering domains [81, 82]. Despite its widespread utility, PVC poses environmental challenges. Its non-biodegradable nature and long lifespan contribute to significant waste management concerns. The incineration of polyvinyl chloride (PVC) waste generates pollutants, including hydrogen chloride gas and, under suboptimal conditions, dioxins. However, contemporary waste-to-energy incinerators, which are equipped with advanced emission control systems, have significantly mitigated these emissions. Despite this progress, the widespread adoption of such technologies continues to pose a challenge [83, 84]. The incorporation of nanocellulose, a renewable and biodegradable material, into PVC matrices significantly improves mechanical properties and thermal stability and reduces environmental impact. However, the hydrophilic nature of nanocellulose, which is attributed to its abundant hydroxyl groups, presents compatibility challenges when combined with hydrophobic polymers such as PVC. These challenges can result in poor dispersion, agglomeration, diminished mechanical performance, and increased moisture sensitivity [85, 86].

1.6 Biodegradation of Polyvinyl Chloride (PVC)-Based Different Fibers Bionanocomposites

PVC can undergo weathering degradation which causes embrittlement and microcracking and leads to the generation of nanoplastics and microplastics which persist for a longer duration of time in the environment. It was discovered that farmland soil samples in China were consistently polluted with various forms of microplastics, especially in open-field agriculture soils (4308 items/kg) with a 40.9% PVC concentration [87, 88]. Bionanocomposites (BNCs) formed by PVC polymer matrix reinforcement with natural fibers are more environmentally friendly than traditional PVC, which are known to contain high chlorine components and considered as potential hazardous material to the ecosystem [89]. Clay-reinforced polyvinyl chloride (PVC) nanocomposites represent a significant advancement in material science, finding utility across a broad range of applications, including the biomedical sector, automotive industry, water purification, packaging, fire protection, and construction [90]. Key clays utilized in the fabrication of these composites include bentonite, montmorillonite, kaolinite, and illite. Incorporating these nanoclays into the PVC matrix enhances its mechanical strength, thermal stability, and yellowness index [91]. Lignin and its derivatives have found great utilization as functional, environmentally friendly fillers in polyvinyl chloride (PVC). Lignin, a complex natural polymer found in plant cell walls, provides essential structural support, rigidity, and protection against microbial attacks [48]. As the second most abundant organic polymer on Earth, after cellulose, lignin is crucial in forming wood and bark, thereby enhancing the plant's strength and durability. Research has explored the partial substitution of PVC with various types of lignin to develop cost-effective materials. These studies have examined both plasticized (soft) and rigid PVC blends [50]. Klapiszewski *et al.* developed a novel SiO_2-lignin hybrid material as a new filler for PVC [92]. They processed PVC compounds as a dry blend with this silica-lignin hybrid material and separately with the individual components used to create the hybrid, utilizing a Brabender mixing chamber for the blending process. Polysaccharides such as cellulose, chitin, glycogen, and starch have been incorporated into PVC to create various blends, offering opportunities to enhance both the properties and sustainability of PVC materials. Cellulose, for example, when blended with PVC, can significantly improve mechanical strength and thermal stability, making it ideal for applications such as biodegradable films and coatings [93].

Cellulose nanocrystals (CNCs), which are derived from renewable sources like wood pulp, are renowned for their high aspect ratio, mechanical strength, and biodegradability. The biodegradation of PVC-based natural fiber-reinforced bionanocomposites is a complex process involving various mechanisms that break down the composite materials into simpler compounds. The degradation of biocomposites is influenced by the chemical, physical, biochemical, and synergistic interaction the polymer matrix, natural fibers, and nanoparticles [94]. It includes the breakdown of covalent bonds in the polymer's backbone, which causes irreversible changes in the chemical and molecular structure of the material, thus breaking down the composite material into simpler byproducts [95]. Biotic degradation occurs due to microbial action, such as bacteria, fungi, and algae [96, 97], that modifies and consumes the polymer or polymeric monomers, producing molecules of low molar mass (terpenes, aldehydes, and acids) and gases (N_2, CH_4, and CO_2). However, surface topography, crystallinity, hydrophobicity, and molecular size of synthetic polymers play a major factor in the biodegradation of the building blocks of plastics [98]. Chemical treatments like alkali treatment (mercerization) are often used to improve fiber–matrix adhesion in composites. These treatments can also alter the biodegradability of the fibers, making the fibers more susceptible to microbial attack [99]. Some fibers may be coated with hydrophobic materials to improve their compatibility with the PVC matrix. While this improves mechanical properties, it can reduce the fiber's biodegradability by limiting microbial access. These organisms are attracted to the natural fibers, which provide organic material for their growth. The initial colonization can lead to the formation of biofilms, which can further contribute to the deterioration of the composite by creating localized microenvironments that promote chemical and biological reactions [100, 101]. Acidic byproducts from microbial activity can also contribute to the chemical deterioration of both the PVC matrix and the natural fibers.

1.7 Polyvinyl Chloride (PVA)-Based Biocomposites and Bionanocomposites for Biomedical Applications

A common thermoplastic polymer for biomedical applications, polyvinyl chloride (PVC) is inexpensive, simple to produce, and has low toxicity [102]. Cardiovascular devices such as artificial heart pumps, blood arteries, dialysis equipment, and catheters are made of PVC [103]. The medical industry makes extensive use of polyvinyl chloride (PVC) thermoplastic polymers, although their applications are somewhat restricted. Other bioactive thermoplastic polymers or biocompatible and bioactive fillers may be added to PVC thermoplastic polymers to improve their characteristics [104]. More than 35 million tons of PVC are produced annually worldwide, and PVC accounts for the majority of medical market materials (blood bags, medical equipment, etc.) [105]. Since synthetic polyvinyl chloride contains hazardous chemical additions like phthalates, lead, cadmium, and organotins, which can be harmful to the health of the environment as well as humans, restrictions on PVC have grown over the past 20 years. These dangerous substances might evaporate or seep into the atmosphere over time. Numerous studies have examined the technique of mixing PVC with different synthetic or natural polymers and inorganic fillers in order to create enhanced PVC materials, such as gels, films, sponges, beads, fibers, sheets, and interconnected polymer (IPN) forms [106]. PVC-hybrid materials exhibit improved mechanical strength and conductivity when combined with nanofillers, which is critical for energy storage applications [107].

In order to enhance the mechanical strength and the electrical and thermal conductivity of PVC, research has focused on the use of various nanofillers over the past decade, such as carbon nanotubes (CNTs), which have high elastic modulus, strength, thermal stability, electrical conductivity, and thermal conductivity [108]. In therapeutic settings, PVC-based mixes, IPNs, and gels are used to treat patients; however, new studies have shown that DEHP, the main plasticizer in PVC, may pose risks. Micropolymers and other advanced biomaterials utilized in tissue engineering must enhance mechanical characteristics and cellular response while also being suitable with biomedical applications [109]. Green PVC blends are suitable for medical applications due to their mechanical properties, resistance to migration, and thermal stability [110]. Along with their long lifespan, PVC-based products have the significant drawback of requiring immediate waste disposal, which can harm the environment [111–113]. Burning waste does not provide a solution to this issue because it releases pollutants into the atmosphere that are dangerous for both people and the environment [114]. Temperature variations may have an impact on the mechanical characteristics of PVC-based WPCs. Closed-loop recycling of wood flour/PVC composites has been researched as a way to cut waste in the production of wood-plastics. According to research, fiber-chain degradation causes bending strength, modulus of elasticity, and impact strength to decrease after four recycling cycles [115]. PVC is an outstanding instance of such polymers, having a high degree of mechanical and chemical resistance, being inert to biological fluids, and being treatable in a variety of ways [116]. Numerous medical devices, including dialysis tubing, lung bypass sets, endotracheal feeds, cannulas, and catheters, employ PVC. Biomaterial-associated infections are becoming more common due to the increasing use of polymeric materials in medical treatment because bacteria or other organisms adhere to the polymer surface and form a pathogenic biofilm.

Several approaches have been shown to be successful in stopping biofilm production, including azide, silver coating, and impregnation of antibacterial compounds into the polymer matrix [117]. In order to develop a biocomposite with improved antimicrobial properties, PVC and gelatin were combined with montmorillonite utilizing a novel antibacterial thermoplastic plasticizer based on the aliphatic anhydride derivative DSA. The remarkable optical, electrical, magnetic, biological, and mechanical properties of composite nanomaterials, coupled with our expanding understanding of fundamental phenomena at the nanoscale, have led to a remarkable increase in interest in these materials in recent years [118]. Green synthesis has recently attracted a lot of attention since environmentally acceptable substitutes for chemical and physical methods for creating nanoparticles have been produced [119]. PVC nanofibers are becoming more popular because of their high porosity, mechanical strength, huge surface area, water resistance, and non-toxicity. Their diameters range from hundreds of nanometers to several micrometers [120]. The biopolymer polyhydroxybutyrate (PHB), which is made by bacteria and archaea, is essential to the bioplastic industry because of its versatility, biodegradability, and environmental friendliness [121]. Dutta *et al.* used rice husk ash (RHA), thermoplastic starch (TPS), and polyvinyl chloride (PVC) as the synthetic matrix to create a bio-based hybrid nanocomposite [122]. The properties of the composite were significantly improved by bio-based additives such as oxidized soybean oil (ESO), tannic acid, calcium oxide (TA-CaO), and organically modified layered double hydroxide (OLDH). The work highlights the potential for creating environmentally friendly materials by demonstrating how nanofillers and bio-based components can be effectively used to enhance the properties of PVC-based composites. A similar study by Dutta & Maji [123] aimed to enhance the value of rice husk by creating composites with microcrystalline cellulose (MCC) and montmorillonite (MMT) using a melt blending process. According to the study, adding MCC and MMT to rice husk-based composites, like PRMCC2, enhances their mechanical and thermal characteristics, making them appropriate for uses requiring strong thermal stability.

1.8 Polyvinyl Chloride (PVC)-Based Hybrid Biocomposites and Bionanocomposites

PVC is a widely used thermoplastic polymer known for its affordability, excellent chemical resistance, flame retardancy, and versatility. Its broad range of applications spans from construction materials (such as pipes and window frames) to healthcare devices and electrical insulation. However, like many synthetic polymers, traditional PVC exhibits poor biodegradability and poses environmental challenges. From an environmental standpoint, PVC-based hybrid biocomposites offer a partial solution to the global plastic waste problem. The use of bio-fillers not only displaces a portion of the petroleum-based polymer but also enables valorization of agricultural waste and natural resources. Furthermore, these composites can be engineered to be recyclable, biodegradable, or biocompatible, depending on the selection of reinforcements and processing techniques. This aligns with the global shift toward a circular economy, where materials are designed for reuse, recycling, or safe degradation at the end of their life cycle. Hybrid-based bionanocomposites represent a frontier in sustainable materials engineering, offering high performance, multifunctionality, and biodegradability. By intelligently combining nano-sized reinforcements of varied origins, researchers can achieve superior mechanical, thermal, and barrier properties while maintaining environmental compatibility. Although technological and economic challenges exist, the ongoing surge in research and innovation indicates that hybrid bionanocomposites will play a pivotal role in the development of next-generation eco-functional materials for a variety of applications.

Polyvinyl chloride (PVC) is a widely used thermoplastic polymer recognized for its chemical resistance, dimensional stability, flame retardancy, and cost-effectiveness. Despite being non-biodegradable, PVC continues to dominate several industrial sectors such as construction, automotive, packaging, and electronics. However, environmental concerns associated with its disposal and plasticizer leaching have led to renewed interest in modifying PVC with eco-friendly reinforcements. In this context, hybrid-based biocomposites, where PVC is reinforced with a combination of natural fibers and other bio-derived or synthetic fillers, offer a compelling solution. These composites seek to bridge the gap between PVC's performance limitations and the need for more sustainable materials by incorporating bio-fillers, agricultural waste fibers, and hybrid nanoparticles to improve mechanical, thermal, and environmental characteristics. The mechanical performance of PVC/hybrid biocomposites is significantly influenced by filler composition, morphology, orientation, and interfacial adhesion. Common trends observed in such composites include the following: PVC/hybrid-based biocomposites represent a powerful evolution in composite materials technology—blending cost-effective, high-performance PVC with natural and inorganic reinforcements to create systems that are mechanically robust, thermally stable, and environmentally conscious. Through intelligent hybridization, these composites overcome the limitations of conventional PVC while reducing ecological footprints. Their growing role in structural, automotive, and consumer applications demonstrates their viability in a world increasingly focused on sustainable development. Bionanocomposites represent a new frontier in materials science, where bio-based materials and nanotechnology converge to enhance mechanical, thermal, and barrier properties of polymer matrices. These materials incorporate nanoscale reinforcements (such as nanoclay, nano-silica, carbon nanotubes, graphene oxide, or metal oxides) along with biodegradable or bio-derived fillers (like cellulose nanocrystals, lignin, chitosan, starch, etc.) into a conventional polymer such as PVC. When applied to PVC systems, hybrid bionanocomposites exploit the flame retardancy, chemical resistance, and structural stability of PVC and augment them using green nanomaterials. This results in lightweight, high-strength composites that can meet the growing demand for eco-efficient and smart materials across multiple industries.

1.9 Preparation and PVC/Rubber Bio Nano Blends

The mentioned rubbers are recognized to indicate numerous properties such as oil resistance, low gas permeability and high mechanical strength. A wide variety of nano additives are used in the PVC/rubber blend for several purposes, of which the most significant are reduction in material cost and improvement in reinforcement and processing. For example, nitrile rubbers are highly miscible with PVC because of near solubility parameters. Blending with PVC exhibits excellent ozone, oil, and flame resistance. Passador and co-workers improved the toughness of PVC using blending with NBR [124]. Yang and co-workers investigated probability of toughening of PVC loaded with $CaCO_3$ nanoparticles. Here, silicone rubber was used an interfacial modifier in order to reduce the incompatibility between polymer–nanoparticle interfaces [125]. Emulsion polymerization is a type of radical addition polymerization that usually happens in a heterogeneous system containing monomer, surfactant, and water. In this process, monomer droplets emulsified in continuous water phase called oil in water emulation, which is the most common type of emulsion. Also, researchers applied this method for preparation of PVC/rubber-based bio nano blend [126]. The operation of elongation flow is based on circulation flows between two opposite cylindrical chambers that are created by removable static mixing element. In this process, all components are discharged into a mixer and mixed at a controlled speed and pressed for preparation of a dry blend of pellets. The determined speed and presser settings depend on components' viscosity [127]. In general, the interfacial adhesion between polymer matrix and nanoparticles results from the blending of PVC/rubber, which has an effective role in the toughening of polymers. Mechanical properties include hardness, strength, modulus of elasticity and fracture toughness, fatigue behavior, and properties that determine the behavior of materials against the forces involved. The existence of nanoparticles in polymer matrix provides a higher surface for the interaction between nanoparticles and the polymer matrix; as a result, it highlights the reinforcement role of nanoparticle in tensile strength [128]. Gheno and co-workers utilized the AFM technique to evaluate the influence dynamically vulcanized PVC/NBR blends on surface morphology. The dark and bright regions related to the valleys and hills of the surface that helped to identify the phase-separated regions. It was observed that the particle size became higher by increasing the NBR content in the blends that were induced by aggregating the NBR particles. We have published some of the research works related to the petroleum-based polymer-biobased composites, nanocomposites and their applications [129–135]. For the future, we have already started some research work on PVC-based biocomposites and bionanocomposites. We are learning from past work and trying to make more improvements in our research work.

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