



International Journal of Polymer Analysis and Characterization

ISSN: 1023-666X (Print) 1563-5341 (Online) Journal homepage: <http://www.tandfonline.com/loi/gpac20>

Recent advances in starch-clay nanocomposites

G. Madhumitha, J. Fowsiya, S. Mohana Roopan & Vijay Kumar Thakur

To cite this article: G. Madhumitha, J. Fowsiya, S. Mohana Roopan & Vijay Kumar Thakur (2018): Recent advances in starch-clay nanocomposites, International Journal of Polymer Analysis and Characterization, DOI: [10.1080/1023666X.2018.1447260](https://doi.org/10.1080/1023666X.2018.1447260)

To link to this article: <https://doi.org/10.1080/1023666X.2018.1447260>



Accepted author version posted online: 05 Mar 2018.



Submit your article to this journal [↗](#)



Article views: 9



View related articles [↗](#)



View Crossmark data [↗](#)



Recent Advances in Starch-Clay Nanocomposites

G. Madhumitha¹, J. Fowsiya¹, S. Mohana Roopan¹, Vijay Kumar Thakur²

¹Chemistry of Heterocycles & Natural Product Research Laboratory, Organic Chemistry Division, School of Advanced Sciences, VIT University, Vellore, Tamilnadu, India,

²Enhanced Composites & Structures Centre, School of Aerospace, Transport and Manufacturing, Cranfield University, Cranfield, Bedfordshire MK43 0AL, England (UK)

Corresponding author: Vijay Kumar Thakur, Email: vijayisu@hotmail.com

Received: 6 February 2018, accepted: 27 February 2018.

Abstract

Biological nanocomposites are a valuable addition to the existing nanocomposite materials and eventually can substitute petroleum based composite materials in numerous applications due to their inherent advantages such as biodegradability, eco-friendliness, low cost and easy availability to name a few. Recently polymer-clay nanocomposites have achieved much more attention due to their enhanced properties such as size dispersion and significant enhancement in physico-chemical and mechanical properties in comparison to the pure polymer systems. Among various biopolymers, starch is one of the most abundant natural polymer on earth and is highly valuable due to its chemical and physical properties. Starch polymer has highly increased potential as an alternative to petroleum based materials. However, starch cannot be used alone and starch-clay nanocomposite have emerged as a new potential green sustainable materials. This article focuses on recent progress in starch based nanocomposites with particular emphasis on starch-clay nanocomposite preparation, properties and applications.

KEYWORDS: Starch, clay, nanocomposites, preparation, properties, applications.

1. INTRODUCTION

Nowadays, most of the petrochemical polymers are highly hazardous to the environment and serious efforts are ongoing to reduce their use[1–6]. The synthesis of such polymers produces hazardous wastes that are not easily degradable, leads to environmental problems including production of high carbon dioxide[7–8,1]. Whereas, plants consist of many polymers that are easily degradable, renewable and eco-friendly[9–10,4]. Different kinds of natural derived biopolymers are abundant and relatively inexpensive[11–13]. The research that has been extremely investigated in the recent years is the development of biodegradable materials including nanocomposites (Figure 1) from renewable sources. The natural derived nanocomposites of polymers provide significant improvements in mechanical and physical properties[14–17]. A composite can be defined as, a material made up of two or more components[18]. Solid multiphase composites can be prepared via combination of various materials in different structure, chemical and physical properties[19]. The unusual combination of component properties such as stiffness, permeability, electrical properties and biodegradability leads to the formation of difficult structure of composite which cannot be separated by individual components. Single phase composites are called as matrix and others are called as fillers which makes the dispersed phase[20–22]. Due to the unique advantages like production, low weight and ductility, polymeric composites have become very familiar than metals and ceramics[14,23]. Polymeric composites can be formed by the combination of natural or synthetic inorganic fillers[24]. Inorganic fillers increase the

properties of the polymers and simply become very low cost. Polymeric composites used in wide range of application in industry as well as research field because of their better mechanical, thermal and fire retardancy efficient properties [25–26]. The efficiency of polymer composites is further improved strongly by the fillers for mechanical, thermal and electrical properties[27]. Platelet clays, carbon nanotubes and nano fibers are commercially available and used nano fillers for polymer composites due to its considerable attention of unique characteristics at low volume fractions[28]. As a result of low fillers and low density of polymers leads to the formation of nanocomposite in particular system[29]. Nanocomposite technology has a great importance in the preparation of synthetic and natural polymers based nanocomposites[30–31]. Toyota has earlier reported on the improved properties of nylon-6 through the exfoliated clay.

A long with the properties of polymers, fillers properties also have an important role in the morphology and properties of the resulting nanocomposite[15,32]. Clays is among one of the main groups of nano-fillers being used due to its improved efficiency than that of conventional fillers [33–35]. There has been another development in the biodegradable materials especially starch which is derived from higher plants that are low cost and biodegradable[36–37]. Furthermore, plasticizers with starches can be processed by conventional thermoplastic techniques. But still the mechanical characteristics of starch based materials are more complex and are highly sensitive to temperature, humidity and pH to name few[38](Chivrac et al., 2010)[39]. This limitation can be overcome by the addition of low amount of clay on starch and the main challenge in the proceedings of starch clay nanocomposites is, to disperse clay into the starch matrix[40–41]. In the

following section we will be discussing different aspects of polymer/clay nanocomposites with particular emphasis on starch based nanocomposites[42–46].

2. POLYMER/CLAY NANOCOMPOSITES

Polymer/clay nanocomposites achieved much more attention in the field of nano research due to the interesting properties which cannot be attained by fillers with micro size[47–50,43]. The improved properties of clay makes pristine polymers of utmost importance in modern polymer industry[51–54]. About 30 % of silicates contains minerals and the silicate structure is SiO_4^- tetrahedron. Central silicon ion has positive charge surrounded by negatively charged oxygen. The silicon and oxygen bond is almost same to the total bond energy of oxygen which leads to the bonding of another silicon ion, continuously linking with another to another silicon ion. Due to the different combination of silicate tetrahedron, it forms a single units (nesosilicates), double units namely sorosilicates, chain units namely inosilicates, sheets (phyllosilicates), rings (cyclosilicates) and framed structure (tectosilicates). The Phyllosilicates or layered or sheet silicates is the most used silicates for nanocomposites. Clays was considered to be an important minerals in the Phyllosilicate or Layered silicates with more percentage of water molecules in silicate layer. Most of the clays are chemically and structurally unique, but they have different quantity of water content which allows more replacement of cations[55–57]. Further clay can be alienated into three primary groups(i) The Kaolinite group(ii) The Smectite group and (iii) The Illite or the Mica-clay group. In polymer nano-composites systems MMT, hectorite and saponite are most frequently used as the reinforcement. Among these MMT is mostly used because of its well –controlled and chemical properties and more

abundant/ inexpensive[58–59]. Two properties of MMT play an important role in the preparation of polymer clay nano composites. First of all, the ability of silicate to be dispersed in layers and second is, their surface chemistry through ion exchange reactions[60]. Most of the clays contain Na^+ and K^+ ions[61–63]. To obtain the biodegradable polymer, it must convert into organophilic one which makes interaction between the hydrophilic polymer such as Poly (ethylene oxide) (PEO)[64] or poly (vinyl alcohol) (PVA)[65] by the ion exchange reactions. Sodium or potassium ions of MMT are dispersed in water uniformly and extend its swelling property by 30 %. When alkyl ammonium/ phosphonium salts are incorporated into the water dispersion, ions of the layer will exchange with the intergallery cations which leads to the insertion of alkyl ammonium/ phosphonium between the layers.

2.1. Types And Methods Of Preparation Of Clay Nanocomposites

Depending on the interaction between the studied polymer matrix and clay as reinforcement, three different polymer nanocomposites can be prepared (a) Intercalated structure based nanocomposites (b) Exfoliated structure based nanocomposite and (c) Flocculated structure based nanocomposites[66–68]. Depending upon the starting materials and processing techniques, preparation of polymer/clay nanocomposites can be accomplished using three different technique as shown below[69–71]. (a) **In -Situ Intercalative Polymerization:** In this method, polymerization is initiated by heating or irradiation or catalyst and the clay is swollen by the liquid monomer or a monomer solution under study [72] (b) **Intercalation of Polymer:** It depends on the solvent system in which the clay particles are swellable as well as the polymer under study is also

soluble (c) **Melt Intercalation:** Due to the absence of organic solvent, this technique is more environmentally friendly and compatible with industry processes. In this method, solvent molecules are desorbed from the silicate layer to allow the incoming polymer chain during the polymerization process.

3. STARCH BASED CLAYNANOCOMPOSITES

Starch is a novel polysaccharide and is considered to be one of the most potential materials due to its readily availability, low cost, biodegradability etc. Mostly starches are isolated from grains such as wheat, corn, rice, potato and tapioca to name a few. The main constituents of starch are amylose and amylopectin that are linked together with α -D-(1-4) and/or α -D-(1-6) linkages[73]. **Figure 2** shows the structure of amylose and amylopectin. Amylose has been found to exhibit a linear structure while amylopectin has a branched structure. Amylopectin forms the major part of the starch while amylose is just between 15-20 %. Generally, the raw starch is not suitable for some applications such as paper industry due to the higher intermolecular hydrogen bonds among the chain. Furthermore, the melting temperature of starch is generally higher than its degradation temperature. To overcome these limitations, the structure of starch is modified or some plasticizers are added to decrease glass transition temperature[74]. The plasticizers are a low molecular weight substance that increases the flexibility of film and processibility when incorporated in the polymer matrix. This molecule also improves the mobility of polymer chain with significant decrease in hydrogen bonding between the polymer chains. Water is also frequently used as a solvent to destroy the granules of starch. At room temperature, although starch remains insoluble in aqueous medium, however at

high temperature an irreversible swelling process namely gelatinization occurs which leads to degradation of amylase and amylopectin. However, the water content and plasticizer properties are strongly dependent on storage condition and this drawback can be solved by using non-volatile plasticizers such as glycerol. When the samples are stored at below glass transition temperature, the sample will undergo physical ageing, poor water resistance and variation in mechanical properties[75]. Although starch offers numerous advantages than synthetic materials, however it is still far of expectations due to its poor mechanical properties[76]. To overcome the disadvantage associated with the pristine starch, the addition of nanofillers in selected amount is a viable approach. The addition of definite amount of nanofillers can significantly improve the physicochemical properties of starch as well the size can also influence the biological activities of starch based materials[77]. In the following section, we have summarized the processing techniques used in the preparation of starch based nanocomposites with special attention to starch/ clay nanocomposites.

3.1. Processing And Applications Of Starch Based Nanocomposites

Starch based nanocomposites are generally processed using two different techniques namely solution casting and extrusion. The solution casting method is the most common and easiest method to prepare starch based nanocomposites in aqueous medium. This method ensures the proper mixing of the nanofillers with starch. In this method, both the mixing absorption and time are significant to ensure homogeneous dispersion of the fillers in the starch matrix. Generally, starch powder, clay and the plasticizer are dispersed in water and the mixture is then boiled for some requisite interval time. In the

past, the solution casting method was used to prepare starch based nanocomposites reinforced with tunicin whiskers employing glycerol as plasticizer. Different ratios of starch and glycerol were used to obtain composite films with a uniform dispersion and the complete mixture was subsequently gelatinized by an autoclave and degassed to prepare films[78]. The same method was also utilized by Mathew & Dufresne, 2002 for the preparation of starch/ tunicin whiskers nanocomposites with sorbitol as plasticizers instead of glycerol[79]. Additional treatments namely sonication, ultra-sonication, and homogenization are also generally used for the dispersion of starch and fillers. The major limitation of the solution casting method is that the polymer needs to be soluble in the same solvent used for dispersion and swelling of the filler. The alternative technique used for casting method is tape casting process and is useful in the manufacturing of ceramics, plastics, papers, and paints. In a typical method of tape casting, suspension is kept in a reservoir with adjustable blade which is connected to micrometric screws. The suspension will cast like thin layer on tape due to the continuous mobility of blade. Extrusion is another important technique that is frequently used for the preparation of starch nanocomposites. Using the hydrophilic fillers, most of the difficulties encountered using starch nanocomposites processing can be overcome easily. The hydrophilic fillers are well-suited with starch/ glycerol and are able to group together in the matrix. A number of researchers have proposed the synthesis of a dry starch/glycerol/nanofiller mixture in absence of water[80]. On the other hand, some other researchers have indicated some issues and proposed the incorporation of hydrophilic fillers into water suspension by propelling the solution into an extrusion stage in which there is a molten polymer[81]. As an example, Hietala et al., have reported their study on the preparation

of cellulose nanofiber gels using starch, plasticizer, lubricant and cellulose[82]. All the components were mixed with more water content and then extruded the obtained dispersion in different concentrations of cellulose nanofiber. The water content in this work was removed by an extruder barrel equipped with two atmospheric vents and vacuum ventilation was proposed.

As stated earlier, starch does not solubilize in water at room temperature and holds its granular structure and an increase of temperature significantly affects its structure. Although starch offers advantages in biomedical applications, its applications in packing and automotive industry application are limited and alone cannot satisfy most of the requirements as such. Hence, it's essential to incorporate some eco-friendly fillers to improve the existing properties of starch. Among different fillers, clay is most abundant, environmental friendly and low cost filler that is frequently used in many applications as fillers. Kaolin was also used as reinforcement to prepare the nanocomposites using thermoplastic starch[83]. The starch was obtained from corn that was plasticized using glycerin in a specific amount. The prepared nanocomposites were characterized for their mechanical properties analysis along with TGA, DSC and water sorption study. From SEM study it was established that strong bonding exists between kaolin and the starch matrix. In addition to the enhanced mechanical properties, the use of clays resulted in an increase in the water resistance characteristics of thermoplastic starch. Biodegradable thermoplastic starch(TPS)/clay hybrids were also prepared using melt intercalation technique[84]. In this study, four types of MMT (three types of organically modified MMT with different ammonium cations and one pristine) were

used. It was found that the unmodified MMT based nanocomposites exhibit better properties than organically modified MMT. This behavior was attributed to the fact that the hydrophilicity of starch matches more with clay hydrophilicity which can be easily dispersed in the starch matrix in comparison to the organically modified MMT. As a result of the higher hydrophilicity of sodium ion-MMT compared to the organically modified MMT, 58 % increment in the space basal was observed compared to less than 10 % increase in the composites with sodium ion-MMT and organically modified MMT respectively.

Green nanocomposites from starch were also prepared using solvent casting method[85]. In this study, the dispersion of clay into starch was demonstrated in detail with dissimilar addition sequences of plasticizer. Wide angle X-ray diffractometry (WAXD) study was carried out to study the extent of dispersion of the fillers in the synthesized nanocomposites. Different characterization techniques namely FT-IR spectroscopy, water absorption studies, mechanical properties and thermal stability were carried out to completely analyse the material properties. It was concluded from this study that incorporation of starch /plasticizer (glycerol) / clay exhibit an imperative impact on the overall properties of the resulting nanocomposites. Starch plasticization without clay lead to the formation of huge composition with low mobility and decreased diffusion of starch into clay matrix.

Thermoplastic starch–clay nanocomposites were prepared using starch that was procured from potato[86]. The potato starch was reinforced with four different types of

clays namely natural sodium montmorillonite, natural hectorite, a hectorite modified with 2-methyl, 2-hydrogenated tallow quaternary ammonium chloride, and kaolinite. These nanocomposites were prepared by melt processing technique. Different characterization techniques were used to study the intercalation behavior and it was observed in the TEM images that the untreated hectorite nanocomposites were partially exfoliated. On the other hand, the treated hectorite nanocomposites exhibited the exfoliated and intercalated structures. Rheology study of the starch–clay nanocomposites was also carried out [87]. In this work, the montmorillonite (MMT) clay was used to reinforce different types of starch (i.e. starch from wheat, potato, corn, and waxy corn) and it was found that the nanocomposites with hydrophilic MMT exhibit good mechanical properties due to its greater intercalation in the gelatinized starch. It was observed that the nanocomposites procured from wheat/ corn starches demonstrated almost the same elastic modulus values on gelatinization. On the other hand, for both the potato and waxy corn starch samples with increase in temperatures the elastic modulus was found to decrease. Melt intercalation was used to prepare the starch/ silicate polycaprolactone blend nanocomposites that was followed by compression molding[88]. Different mechanical properties of the nanocomposites were investigated in detail. The interaction between dissimilar components of the starch nanocomposites was thoroughly investigated using scanning electron microscopy, dynamic mechanical analysis, X-ray diffraction, and tensile strength testing. It was demonstrated using X-ray diffraction analysis that the polymeric chains and clays were strongly intercalated. Similarly, the effect of glycerol content on the structure and properties of starch/clay nanocomposites was also studied in detail[89]. In this work, melt extrusion processing was employed to prepare the

nanocomposites using corn starch and montmorillonite (MMT) nanoclay. The prepared nanocomposites were thoroughly characterized for their structure and properties analysis by transmission electron microscopy (TEM), X-ray diffraction (XRD), thermogravimetric analysis (TGA) and barrier/ mechanical properties measurement. The plasticized nanocomposite films of starch–clay were found to exhibit higher glass transition temperature (54.74 °C), lower water vapor permeability (0.58 g mm/kPa h m²), and advanced tensile strength of (26.64 MPa). As a conventional plasticizer, the influence of glycerol content was first investigated. With the glycerol concentration up to 5 wt%, the nanocomposites can be prepared by twin screw extruder. However, the degree of clay exfoliation was found to decrease with further increase in glycerol content (20 %) as the higher glycerol content increases the spacing between starch and glycerol that subsequently decreases the attractive force of starch and clay. From this study it was demonstrated that the performance of nanocomposite films is significantly affected by the strong polar–polar interactions among plasticizer, clay surface, and starch. Clay was incorporated into starch to form new nanocomposites with enhanced properties[90]. In this study the polymer matrix was starch that was procured from potato starch, while the mixtures of glycerol and a urea/ethanolamine were used as plasticizers. Polymer nanocomposites were prepared using the neat starch as well as 20 wt % plasticized starch with 6 wt % organically modified montmorillonite nanoclay as well as the pristine montmorillonite. The montmorillonite nanoclay was modified with methyl tallow bis-2-hydroxyethyl quaternary ammonium. Although there was no notable enhancement in the thermal stability of the matrices after the addition of nanoclay, there was an enhancement in the dispersion of MMT-Na⁺ as compared to MMT-OH. These results were supported

by the TEM and XRD results. Water sorption and oxygen permeability studied was also carried out and it was found that the oxygen permeability were higher for the plasticized films compared to the pristine films.

The effect of processing conditions as well as of citric acid on the performance of starch based nanocomposites was also studied[91]. In this work, a facile two step melt extrusion for intercalation of starch in clay galleries was reported. The nanocomposites were prepared using the glycerol modified-montmorillonite (GMMT)/ pristine montmorillonite (PMMT) and thermoplastic starch (TPS). In a typical method, the first step involved the blending of pristine MMT/ glycerol mixture with emulsifying machine (high speed). Subsequently, the modified MMT was also mixed with TPS at different compositions for intercalation and excellent tensile strength analysis. From the transmission electron microscopy (TEM) and X-ray diffraction (XRD) study it was demonstrated that glycerol facilitates the d-spacing as well as leads to the destruction of the montmorillonite (MMT) structure. **Figures 3** shows the TEM micrographs of the studied nanocomposites. Furthermore, the citric acid was found to enhance the TPS plasticization as well as increase in the mechanical properties of the nanocomposites. Biodegradable starch–clay nanocomposites were prepared by incorporating a dilute clay dispersion to a starch solution that was followed by co-precipitation in ethanol[92]. This process leads to nanocomposites with well-dispersed starch–clay. **Figure 4(a)** depicts the synthesis of starch-clay nanocomposites. One of the significant advantages of this technique was that the intercalation of the plasticizer (glycerol) in clay was minimized in this work that is generally required during hot-pressing. It was also found that the starch crystalline

structure was not significantly influenced (**Figure4b**). However, the enhanced dispersion between montmorillonite/polymer matrix increases the interaction between starch molecules/ clays and resulted in higher mechanical properties as a result of the stress transfer to the reinforcement phase. The Chitosan modified clay and corn starch nanocomposites prepared at pH of 4.9 showed improvement modulus and strength. The increase in modulus/ strength of the nanocomposites was 65 % and 30 % respectively for the nanocomposite containing 5 wt% clay in comparison to the pristine starch material. Subsequent increase in clay content resulted in weakening the properties as a result of poorer dispersion of clay and low polymer crystallinity.

The same research groups have also reported their studies on the starch-layered double hydroxide (LDH) nanocomposite[93]. In this work, nanocomposites were prepared by a new technique in which LDH was directly synthesized in the dispersion of starch. An acid modification technique was also used to reduce the molecular weight/ pasting viscosity of the starch that significantly facilitated the LDH crystallites dispersion in the starch nanocomposites. The nanocomposites prepared using the acid modified corn starch (AMS) were also investigated for their mechanical properties. It was found that the crystalline structure of starch was not much affected by the LDH, its high concentration improved the separation in starch but not AMS. Both the nanocomposite showed no change in transparency/ moisture sensitivity however there was a significant increase in the modulus of the nanocomposites. Solution casting method was used to prepare the starch/clay nanocomposites in which the effects of clay cation, starch source, glycerol content as well as the mode of mixing on intercalation of clay was studied[94]. In

addition, the mechanical properties of the nanocomposites were also studied using a Taguchi experimental design approach. Citric acid was also used to modify the clay and the properties were compared for both the pristine/ modified clay based nanocomposites. The citric acid modified clay was found to exhibit better mechanical property when compared with clay. The enhancement in properties was attributed to strong interaction among starch and citric acid molecules. Plasticized starch/ polypropylene blends clay nanocomposites were prepared to overcome the disadvantages associated with plasticized starch (PLS)[95]. In this work, two types of clay i.e. unmodified/organically modified montmorillonite clays, MMT and Cloisite 30B were used to reinforce the plasticized starch/ polypropylene blends. It was found that the MMT has good dispersion in TPS phase of blends while the Cloisite 30B can locate within both TPS and polypropylene. With high content of TPS, the clay significantly increased the tensile strength/ tensile modulus (by an order of magnitude). This behavior was attributed to the reinforcing effect of clay as well as change in the morphology of the two phases as a result of incorporation of clay. Cassava starch based biodegradable films and their nanocomposites were also prepared[96]. Effect of incorporation of glycerol (along with the method of incorporation) on tensile/barrier properties of the prepared films (BF) was studied and analysed in detail. The optimized studies on content of glycerol showed that glycerol and clay content significantly involved in the tensile properties and glass transition temperature. In the case of pristine starch films, the films with lower amount of glycerol exhibited better mechanical and barrier properties. It was concluded from this study that the cassava starch/ clay nanoparticles have the potential to be used as novel biodegradable for packaging applications.

Water barrier properties of starch-clay nanocomposite films were studied by incorporating the Montmorillonite nanoclay in the polymer matrix employing two different morphologies[97]. The effect of clay concentration on the physicochemical properties of the resulting nanocomposite films was studied in detail. It was found that the addition of clay (MMT) content decreased the water permeability due to an increase in the tortuosity and hydrophilicity of the diffusion path caused by clay particles. The opacity was also found to be dependent on the used nanoclay dispersion method. Effect of the hydrophilicities of different clays on the properties of starch-clay nanocomposites was studied in detail[98]. The nanocomposites in this study were prepared using hydroxypropyl distarch phosphate and five different kinds of clays employing the film blowing technique. These nanocomposites were characterized using transmission electron microscopy (TEM) and X-ray diffraction (XRD). It was confirmed from the study that there was a formation of intercalation nanostructure in the nanocomposites. The prepared nanocomposites demonstrated significant improvement in tensile strength/ better barrier properties/ water vapor in comparison to the pristine film. The starch-clay films had a lower glass transition temperature (T_g) and better heat endurance compared to the contrast film. The microstructure of the films was more homogeneous and smooth with the addition of clays into starch. The clay which had a medium hydrophilic property was more suitable for the preparation of hydroxypropyl distarch phosphate-clay nanocomposite films as an intensifier among all the five clays. Biodegradation of the starch nanocomposites was also studied. The effect of incorporation of amount of glycerol on the tensile and barrier properties of the nanocomposites was studied in

detail[96]. The starch used in this work was obtained from cassava starch and the glycerol content was found to significantly affect the barrier and tensile properties[96]. Starch clay nanocomposites were also prepared using acetylation of starch[99]. The nanocomposites were prepared using acetylated corn starch (ACS)/clay (NaMMT) and with or without addition of polyvinyl alcohol (PVOH). In this study also glycerol was used as a plasticizer. To study the intercalated nanocomposite structure, XRD study was carried out in detail in addition to the thermomechanical and mechanical properties. It was found that the addition of clay has a significant reinforcing effects in the starch. Furthermore the replacement of glycerol with polyvinyl alcohol resulted in enhanced mechanical strength as a result of the strong hydrogen bonding between polyvinyl alcohol and starch. Starch-MMT clay nanocomposite were also prepared using screw extruder technique for packaging applications[100]. Citric acid was used to modify the surface characteristics of MMT in order to have a better compatibility among the silicate layers and starch modification. The extent of modification was confirmed by employing X-ray diffraction (XRD) analysis through the expanded microstructure of citric acid-modified MMT (CMMT). In this work, the effect of different reaction parameters including amount of poly (vinyl alcohol)/ CMMT, screw speed along with the temperature profile in the extruder on the tensile strength was studied using Taguchi experimental design. It was concluded from the study that PVA/ CMMT content and screw speed has the significant effect on the overall properties especially on the tensile strength property. Antimicrobial nanostructured starch based nanocomposites films were also prepared for packaging applications by directly synthesizing silver nanoparticles in starch and in clay/starch solutions employing chemical reduction method. [101]. In this study, the

effect of the incorporation of clay and silver nanoparticles was investigated in detail.

Different kinds of nanocomposites films such as silver nanoparticles/starch nanocomposite (Ag-NPs/ST-NC), montmorillonite modified with a quaternary ammonium salt C30B/starch nanocomposite (C30B/ST-NC) and both silver nanoparticles/C30B/starch nanocomposites (Ag-NPs/C30B/ST-NC) were produced.

Figure 5 (a) shows the nanostructured starch films. The effect of amount of different concentration of silver nanoparticles (Ag-NPs (0.3, 0.5, 0.8 and 1.0 mM) was also studied. Different characterization techniques such as X-ray diffraction and scanning electron microscopy were used to confirm the presence of Ag-NPs enhanced clay dispersion (**Figure 5b**). In addition, other properties such as barrier properties (water vapor/ oxygen permeability's), colour and opacity measurements, contact angle and dynamic mechanical analysis were also evaluated. All these measurement were correlated with the incorporation of C30B and Ag-NPs. Subsequently, the antimicrobial activity of the starch films was studied against Staphylococcus aureus, Escherichia coli and Candida albicans without significant differences between Ag-NPs concentrations and it was observed that all the films exhibit promising antimicrobial properties.

CONCLUSION

In this article, a review of most important and recent research on development of biodegradable nanocomposites based on polymer/clay, starch/polymer and starch/clay nanocomposites were exposed. Particularly, the investigation was focused on influences of starch and clay with different biodegradable polymer and starch/clay nanocomposites from renewable source. Some of the different methods of preparation of clay-polymer

and starch based nanocomposites and starch/clay nanocomposites paid significant attention for the further studies. Many physicochemical properties as structure, mechanical property, biodegradation, gas barrier and water permeability have been presented. From the literature about the improvement of nanocomposites, the biodegradable and nanocomposites from renewable sources have more importance than synthetic polymer based nanocomposites. More interestingly, starch-clay nanocomposites have achieved better mechanical property and tensile strength for packaging materials. From the result of literature works cited in this work, it can be concluded that in order to improve the barrier, mechanical and thermal properties of starch/clay matrix, the next consideration need to be taken into account includes morphological and chemical properties of plasticizers and nanofillers. Furthermore, increasing application of synthetic polymer based nanocomposites affects the human population and standard of living. Therefore, use of starch/clay nanocomposites may alter all the limitation of synthetic polymers. As a result of the current progress in sustainable nanocomposites, starch/clay nanocomposites has more importance and that may lead to more research work in the particular field of developing nanocomposites.

ACKNOWLEDGEMENT

The authors would like to thank VIT University, Vellore and DST-FTYS (No. SB/FT/CS-113/2013) for the financial support.

REFERENCES

1. Thakur VK, Lin M-F, Tan EJ, Lee PS (2012) Green aqueous modification of fluoropolymers for energy storage applications. *J Mater Chem* 22:5951–5959. doi: 10.1039/c2jm15665b
2. Thakur VK, Yan J, Lin M-F, et al (2012) Novel polymer nanocomposites from bioinspired green aqueous functionalization of BNNTs. *Polym Chem* 3:962–969. doi: 10.1039/c2py00612j
3. Thakur VK, Tan EJ, Lin M-F, Lee PS (2011) Polystyrene grafted polyvinylidene fluoride copolymers with high capacitive performance. *Polym Chem* 2:2000–2009. doi: 10.1039/c1py00225b
4. Avella M, De Vlieger JJ, Errico ME, et al (2005) Biodegradable starch/clay nanocomposite films for food packaging applications. *Food Chem* 93:467–474. doi: 10.1016/j.foodchem.2004.10.024
5. Park H-M, Lee W-K, Park C-Y, et al (2003) Environmentally friendly polymer hybrids Part I Mechanical, thermal, and barrier properties of thermoplastic starch/clay nanocomposites. *J Mater Sci* 38:909–915. doi: 10.1023/A:1022308705231
6. Zhang Q-X, Yu Z-Z, Xie X-L, et al (2007) Preparation and crystalline morphology of biodegradable starch/clay nanocomposites. *Polymer* 48:7193–7200. doi: 10.1016/j.polymer.2007.09.051
7. Singha AS, Thakur VK (2008) Synthesis and Characterization of Pine Needles Reinforced RF Matrix Based Biocomposites. *J Chem* 5:1055–1062. doi: 10.1155/2008/395827

8. Thakur VK, Tan EJ, Lin M-F, Lee PS (2011) Poly(vinylidene fluoride)-graft-poly(2-hydroxyethyl methacrylate): a novel material for high energy density capacitors. *J Mater Chem* 21:3751–3759. doi: 10.1039/c0jm02408b
9. Pappu A, Patil V, Jain S, et al (2015) Advances in industrial prospective of cellulosic macromolecules enriched banana biofibre resources: A review. *Int J Biol Macromol* 79:449–458. doi: 10.1016/j.ijbiomac.2015.05.013
10. Thakur VK, Thakur MK (2015) Recent advances in green hydrogels from lignin: a review. *Int J Biol Macromol* 72:834–847. doi: 10.1016/j.ijbiomac.2014.09.044
11. Thakur VK, Thakur MK (2014) Recent Advances in Graft Copolymerization and Applications of Chitosan: A Review. *Acs Sustain Chem Eng* 2:2637–2652. doi: 10.1021/sc500634p
12. Thakur VK, Thakur MK (2014) Recent trends in hydrogels based on psyllium polysaccharide: a review. *J Clean Prod* 82:1–15. doi: 10.1016/j.jclepro.2014.06.066
13. Chen M, Chen B, Evans JRG (2005) Novel thermoplastic starch–clay nanocomposite foams. *Nanotechnology* 16:2334. doi: 10.1088/0957-4484/16/10/056
14. Jordan J, Jacob KI, Tannenbaum R, et al (2005) Experimental trends in polymer nanocomposites—a review. *Mater Sci Eng A* 393:1–11. doi: 10.1016/j.msea.2004.09.044
15. Thakur VK, Vennerberg D, Kessler MR (2014) Green Aqueous Surface Modification of Polypropylene for Novel Polymer Nanocomposites. *Acs Appl Mater Interfaces* 6:9349–9356. doi: 10.1021/am501726d
16. Majdzadeh-Ardakani K, Nazari B (2010) Improving the mechanical properties of thermoplastic starch/poly(vinyl alcohol)/clay nanocomposites. *Compos Sci Technol* 70:1557–1563. doi: 10.1016/j.compscitech.2010.05.022

17. Cyras VP, Manfredi LB, Ton-That M-T, Vázquez A (2008) Physical and mechanical properties of thermoplastic starch/montmorillonite nanocomposite films. *Carbohydr Polym* 73:55–63. doi: 10.1016/j.carbpol.2007.11.014
18. Thakur VK, Kessler MR (2014) Synthesis and Characterization of AN-g-SOY for Sustainable Polymer Composites. *ACS Sustain Chem Eng* 2:2454–2460. doi: 10.1021/sc500473a
19. Thakur VK, Thakur MK, Gupta RK (2014) Graft copolymers of natural fibers for green composites. *Carbohydr Polym* 104:87–93. doi: 10.1016/j.carbpol.2014.01.016
20. Singha AS, Thakur VK (2008) Sacccharum Cilliare Fiber Reinforced Polymer Composites. *E-J Chem* 5:782–791.
21. Singha AS, Thakur VK (2009) Fabrication and characterization of S-cilliare fibre reinforced polymer composites. *Bull Mater Sci* 32:49–58. doi: 10.1007/s12034-009-0008-x
22. Magalhães NF, Andrade CT (2009) Thermoplastic corn starch/clay hybrids: Effect of clay type and content on physical properties. *Carbohydr Polym* 75:712–718. doi: 10.1016/j.carbpol.2008.09.020
23. Lin M-F, Thakur VK, Tan EJ, Lee PS (2011) Dopant induced hollow BaTiO₃ nanostructures for application in high performance capacitors. *J Mater Chem* 21:16500–16504. doi: 10.1039/c1jm12429c
24. Lin M-F, Thakur VK, Tan EJ, Lee PS (2011) Surface functionalization of BaTiO₃ nanoparticles and improved electrical properties of BaTiO₃/polyvinylidene fluoride composite. *Rsc Adv* 1:576–578. doi: 10.1039/c1ra00210d

25. Panamoottil SM, Poetschke P, Lin RJT, et al (2013) Conductivity of microfibrillar polymer-polymer composites with CNT-loaded microfibrils or compatibilizer: A comparative study. *Express Polym Lett* 7:607–620. doi: 10.3144/expresspolymlett.2013.58
26. Azmi AI, Lin RJT, Bhattacharyya D (2012) Experimental Study of Machinability of GFRP Composites by End Milling. *Mater Manuf Process* 27:1045–1050. doi: 10.1080/10426914.2012.677917
27. Cardoso SM, O’Connell CD, Pivonka R, et al (2014) Effect of external loads on damage detection of rubber-toughened nanocomposites using carbon nanotubes sensory network. *Polym Compos* n/a-n/a. doi: 10.1002/pc.23188
28. Wanasekara ND, Chalivendra VB (2011) Role of surface roughness on wettability and coefficient of restitution in butterfly wings. *Soft Matter* 7:373–379. doi: 10.1039/c0sm00548g
29. Sun L, Wanasekara N, Chalivendra V, Calvert P (2015) Nano-Mechanical Studies on Polyglactin Sutures Subjected to In Vitro Hydrolytic and Enzymatic Degradation. *J Nanosci Nanotechnol* 15:93–99. doi: 10.1166/jnn.2015.9073
30. Amiralian N, Annamalai PK, Memmott P, Martin DJ (2015) Isolation of cellulose nanofibrils from *Triodia pungens* via different mechanical methods. *Cellulose* 22:2483–2498. doi: 10.1007/s10570-015-0688-x
31. Lima-Tenório MK, Tenório-Neto ET, Guilherme MR, et al (2015) Water transport properties through starch-based hydrogel nanocomposites responding to both pH and a remote magnetic field. *Chem Eng J* 259:620–629. doi: 10.1016/j.cej.2014.08.045

32. Thakur VK, Kessler MR (2015) Self-healing polymer nanocomposite materials: A review. *Polymer* 69:369–383. doi: 10.1016/j.polymer.2015.04.086
33. LeBaron PC, Wang Z, Pinnavaia TJ (1999) Polymer-layered silicate nanocomposites: an overview. *Appl Clay Sci* 15:11–29. doi: 10.1016/S0169-1317(99)00017-4
34. Mondragón M, Mancilla JE, Rodríguez-González FJ (2008) Nanocomposites from plasticized high-amylopectin, normal and high-amylose maize starches. *Polym Eng Sci* 48:1261–1267. doi: 10.1002/pen.21084
35. Wu J, Lin J, Zhou M, Wei C (2000) Synthesis and properties of starch-graft-polyacrylamide/clay superabsorbent composite. *Macromol Rapid Commun* 21:1032–1034. doi: 10.1002/1521-3927(20001001)21:15<1032::AID-MARC1032>3.0.CO;2-N
36. Eğri Ö, Salimi K, Eğri S, et al (2016) Fabrication and characterization of novel starch-grafted poly l-lactic acid/montmorillonite organoclay nanocomposites. *Carbohydr Polym* 137:111–118. doi: 10.1016/j.carbpol.2015.10.043
37. Babae M, Jonoobi M, Hamzeh Y, Ashori A (2015) Biodegradability and mechanical properties of reinforced starch nanocomposites using cellulose nanofibers. *Carbohydr Polym* 132:1–8. doi: 10.1016/j.carbpol.2015.06.043
38. Cheviron P, Gouanvé F, Espuche E (2015) Starch/silver nanocomposite: Effect of thermal treatment temperature on the morphology, oxygen and water transport properties. *Carbohydr Polym* 134:635–645. doi: 10.1016/j.carbpol.2015.07.067
39. Kalambur SB, Rizvi SS (2004) Starch-based nanocomposites by reactive extrusion processing. *Polym Int* 53:1413–1416. doi: 10.1002/pi.1478

40. Vertuccio L, Gorrasi G, Sorrentino A, Vittoria V (2009) Nano clay reinforced PCL/starch blends obtained by high energy ball milling. *Carbohydr Polym* 75:172–179. doi: 10.1016/j.carbpol.2008.07.020
41. Almasi H, Ghanbarzadeh B, Entezami AA (2010) Physicochemical properties of starch–CMC–nanoclay biodegradable films. *Int J Biol Macromol* 46:1–5. doi: 10.1016/j.ijbiomac.2009.10.001
42. Aouada FA, Mattoso LHC, Longo E (2011) New strategies in the preparation of exfoliated thermoplastic starch–montmorillonite nanocomposites. *Ind Crops Prod* 34:1502–1508. doi: 10.1016/j.indcrop.2011.05.003
43. Chivrac F, Pollet E, Schmutz M, Avérous L (2008) New Approach to Elaborate Exfoliated Starch-Based Nanobiocomposites. *Biomacromolecules* 9:896–900. doi: 10.1021/bm7012668
44. Liu H, Chaudhary D, Yusa S, Tade MO (2011) Glycerol/starch/Na⁺-montmorillonite nanocomposites: A XRD, FTIR, DSC and ¹H NMR study. *Carbohydr Polym* 83:1591–1597. doi: 10.1016/j.carbpol.2010.10.018
45. Müller CMO, Laurindo JB, Yamashita F (2011) Effect of nanoclay incorporation method on mechanical and water vapor barrier properties of starch-based films. *Ind Crops Prod* 33:605–610. doi: 10.1016/j.indcrop.2010.12.021
46. Mbey JA, Hoppe S, Thomas F (2012) Cassava starch–kaolinite composite film. Effect of clay content and clay modification on film properties. *Carbohydr Polym* 88:213–222. doi: 10.1016/j.carbpol.2011.11.091

47. Zare Y (2015) Estimation of material and interfacial/interphase properties in clay/polymer nanocomposites by yield strength data. *Appl Clay Sci* 115:61–66. doi: 10.1016/j.clay.2015.07.021
48. Emre FB, Kesik M, Kanik FE, et al (2015) A benzimidazole-based conducting polymer and a PMMA–clay nanocomposite containing biosensor platform for glucose sensing. *Synth Met* 207:102–109. doi: 10.1016/j.synthmet.2015.06.015
49. Huang M-F, Yu J-G, Ma X-F (2004) Studies on the properties of Montmorillonite-reinforced thermoplastic starch composites. *Polymer* 45:7017–7023. doi: 10.1016/j.polymer.2004.07.068
50. Ma X, Yu J, Wang N (2007) Production of Thermoplastic Starch/MMT-Sorbitol Nanocomposites by Dual-Melt Extrusion Processing. *Macromol Mater Eng* 292:723–728. doi: 10.1002/mame.200700026
51. Anadao P (2012) *Polymer/ Clay Nanocomposites: Concepts, Researches, Applications and Trends for The Future. Nanocomposites - New Trends Dev.*
52. Pérez CJ, Alvarez VA, Vázquez A (2008) Creep behaviour of layered silicate/starch–polycaprolactone blends nanocomposites. *Mater Sci Eng A* 480:259–265. doi: 10.1016/j.msea.2007.07.031
53. Chivrac F, Gueguen O, Pollet E, et al (2008) Micromechanical modeling and characterization of the effective properties in starch-based nano-biocomposites. *Acta Biomater* 4:1707–1714. doi: 10.1016/j.actbio.2008.05.002
54. Liao H-T, Wu C-S (2005) Synthesis and characterization of polyethylene-octene elastomer/clay/biodegradable starch nanocomposites. *J Appl Polym Sci* 97:397–404. doi: 10.1002/app.21763

55. Huang M, Yu J, Ma X (2006) High mechanical performance MMT-urea and formamide-plasticized thermoplastic cornstarch biodegradable nanocomposites. *Carbohydr Polym* 63:393–399. doi: 10.1016/j.carbpol.2005.09.006
56. Ikeo Y, Aoki K, Kishi H, et al (2006) Nano clay reinforced biodegradable plastics of PCL starch blends. *Polym Adv Technol* 17:940–944. doi: 10.1002/pat.816
57. Namazi H, Mosadegh M, Dadkhah A (2009) New intercalated layer silicate nanocomposites based on synthesized starch-g-PCL prepared via solution intercalation and in situ polymerization methods: As a comparative study. *Carbohydr Polym* 75:665–669. doi: 10.1016/j.carbpol.2008.09.006
58. Kalambur S, Rizvi SSH (2005) Biodegradable and functionally superior starch–polyester nanocomposites from reactive extrusion. *J Appl Polym Sci* 96:1072–1082. doi: 10.1002/app.21504
59. Perotti GF, Tronto J, Bizeto MA, et al (2014) Biopolymer-clay nanocomposites: cassava starch and synthetic clay cast films. *J Braz Chem Soc* 25:320–330. doi: 10.5935/0103-5053.20130300
60. Maisanaba S, Pichardo S, Puerto M, et al (2015) Toxicological evaluation of clay minerals and derived nanocomposites: A review. *Environ Res* 138:233–254. doi: 10.1016/j.envres.2014.12.024
61. Wang W, Wang A (2016) Recent progress in dispersion of palygorskite crystal bundles for nanocomposites. *Appl Clay Sci* 119, Part 1:18–30. doi: 10.1016/j.clay.2015.06.030

62. Bocchini S, Battegazzore D, Frache A (2010) Poly (butylensuccinate co-adipate)-thermoplastic starch nanocomposite blends. *Carbohydr Polym* 82:802–808. doi: 10.1016/j.carbpol.2010.05.056
63. B. A, Suin S, Khatua BB (2014) Highly exfoliated eco-friendly thermoplastic starch (TPS)/poly (lactic acid)(PLA)/clay nanocomposites using unmodified nanoclay. *Carbohydr Polym* 110:430–439. doi: 10.1016/j.carbpol.2014.04.024
64. Ogata N, Kawakage S, Ogihara T (1997) Poly(vinyl alcohol)-clay and poly(ethylene oxide)-clay blends prepared using water as solvent. *J Appl Polym Sci* 66:573–581. doi: 10.1002/(SICI)1097-4628(19971017)66:3<573::AID-APP19>3.0.CO;2-W
65. Fischer H (2003) Polymer nanocomposites: from fundamental research to specific applications. *Mater Sci Eng C* 23:763–772. doi: 10.1016/j.msec.2003.09.148
66. Lee SY, Chen H, Hanna MA (2008) Preparation and characterization of tapioca starch–poly(lactic acid) nanocomposite foams by melt intercalation based on clay type. *Ind Crops Prod* 28:95–106. doi: 10.1016/j.indcrop.2008.01.009
67. Dean KM, Do MD, Petinakis E, Yu L (2008) Key interactions in biodegradable thermoplastic starch/poly(vinyl alcohol)/montmorillonite micro- and nanocomposites. *Compos Sci Technol* 68:1453–1462. doi: 10.1016/j.compscitech.2007.10.037
68. McGlashan SA, Halley PJ (2003) Preparation and characterisation of biodegradable starch-based nanocomposite materials. *Polym Int* 52:1767–1773. doi: 10.1002/pi.1287

69. Kampeerapappun P, Aht-ong D, Pentrakoon D, Srikulkit K (2007) Preparation of cassava starch/montmorillonite composite film. *Carbohydr Polym* 67:155–163. doi: 10.1016/j.carbpol.2006.05.012
70. Schlemmer D, Angélica RS, Sales MJA (2010) Morphological and thermomechanical characterization of thermoplastic starch/montmorillonite nanocomposites. *Compos Struct* 92:2066–2070. doi: 10.1016/j.compstruct.2009.10.034
71. Barzegar H, Azizi MH, Barzegar M, Hamidi-Esfahani Z (2014) Effect of potassium sorbate on antimicrobial and physical properties of starch–clay nanocomposite films. *Carbohydr Polym* 110:26–31. doi: 10.1016/j.carbpol.2014.03.092
72. Olad A, Rashidzadeh A (2008) Preparation and anticorrosive properties of PANI/Na-MMT and PANI/O-MMT nanocomposites. *Prog Org Coat* 62:293–298. doi: 10.1016/j.porgcoat.2008.01.007
73. Zia F, Zia KM, Zuber M, et al (2015) Starch based polyurethanes: A critical review updating recent literature. *Carbohydr Polym* 134:784–798. doi: 10.1016/j.carbpol.2015.08.034
74. Sweedman MC, Tizzotti MJ, Schäfer C, Gilbert RG (2013) Structure and physicochemical properties of octenyl succinic anhydride modified starches: A review. *Carbohydr Polym* 92:905–920. doi: 10.1016/j.carbpol.2012.09.040
75. Doi Y (1995) Microbial synthesis, physical properties, and biodegradability of polyhydroxyalkanoates. *Macromol Symp* 98:585–599. doi: 10.1002/masy.19950980150
76. Hansen NML, Plackett D (2008) Sustainable Films and Coatings from Hemicelluloses: A Review. *Biomacromolecules* 9:1493–1505. doi: 10.1021/bm800053z

77. Lu Y, Weng L, Cao X (2006) Morphological, thermal and mechanical properties of ramie crystallites—reinforced plasticized starch biocomposites. *Carbohydr Polym* 63:198–204. doi: 10.1016/j.carbpol.2005.08.027
78. Anglès MN, Dufresne A (2000) Plasticized Starch/Tunicin Whiskers Nanocomposites. 1. Structural Analysis. *Macromolecules* 33:8344–8353. doi: 10.1021/ma0008701
79. Mathew AP, Dufresne A (2002) Plasticized Waxy Maize Starch: Effect of Polyols and Relative Humidity on Material Properties. *Biomacromolecules* 3:1101–1108. doi: 10.1021/bm020065p
80. Galicia-García T, Martínez-Bustos F, Jiménez-Arévalo OA, et al (2012) Films of native and modified starch reinforced with fiber: Influence of some extrusion variables using response surface methodology. *J Appl Polym Sci* 126:E327–E336. doi: 10.1002/app.36982
81. Avérous L, Pollet E (2012) *Environmental Silicate Nano-Biocomposites*. Springer London, London
82. Hietala M, Mathew AP, Oksman K (2013) Bionanocomposites of thermoplastic starch and cellulose nanofibers manufactured using twin-screw extrusion. *Eur Polym J* 49:950–956. doi: 10.1016/j.eurpolymj.2012.10.016
83. de Carvalho AJF, Curvelo AAS, Agnelli JAM (2001) A first insight on composites of thermoplastic starch and kaolin. *Carbohydr Polym* 45:189–194. doi: 10.1016/S0144-8617(00)00315-5

84. Park H-M, Li X, Jin C-Z, et al (2002) Preparation and Properties of Biodegradable Thermoplastic Starch/Clay Hybrids. *Macromol Mater Eng* 287:553–558. doi: 10.1002/1439-2054(20020801)287:8<553::AID-MAME553>3.0.CO;2-3
85. Pandey JK, Singh RP (2005) Green Nanocomposites from Renewable Resources: Effect of Plasticizer on the Structure and Material Properties of Clay-filled Starch. *Starch - Stärke* 57:8–15. doi: 10.1002/star.200400313
86. Chen B, Evans JRG (2005) Thermoplastic starch–clay nanocomposites and their characteristics. *Carbohydr Polym* 61:455–463. doi: 10.1016/j.carbpol.2005.06.020
87. Chiou B-S, Yee E, Glenn GM, Orts WJ (2005) Rheology of starch–clay nanocomposites. *Carbohydr Polym* 59:467–475. doi: 10.1016/j.carbpol.2004.11.001
88. Pérez CJ, Alvarez VA, Mondragón I, Vázquez A (2007) Mechanical properties of layered silicate/starch polycaprolactone blend nanocomposites. *Polym Int* 56:686–693. doi: 10.1002/pi.2192
89. Tang X, Alavi S, Herald TJ (2008) Effects of plasticizers on the structure and properties of starch–clay nanocomposite films. *Carbohydr Polym* 74:552–558. doi: 10.1016/j.carbpol.2008.04.022
90. Zeppa C, Gouanvé F, Espuche E (2009) Effect of a plasticizer on the structure of biodegradable starch/clay nanocomposites: Thermal, water-sorption, and oxygen-barrier properties. *J Appl Polym Sci* 112:2044–2056. doi: 10.1002/app.29588
91. Wang N, Zhang X, Han N, Bai S (2009) Effect of citric acid and processing on the performance of thermoplastic starch/montmorillonite nanocomposites. *Carbohydr Polym* 76:68–73. doi: 10.1016/j.carbpol.2008.09.021

92. Chung Y-L, Ansari S, Estevez L, et al (2010) Preparation and properties of biodegradable starch–clay nanocomposites. *Carbohydr Polym* 79:391–396. doi: 10.1016/j.carbpol.2009.08.021
93. Chung Y-L, Lai H-M (2010) Preparation and properties of biodegradable starch-layered double hydroxide nanocomposites. *Carbohydr Polym* 80:525–532. doi: 10.1016/j.carbpol.2009.12.020
94. Majdzadeh-Ardakani K, Navarchian AH, Sadeghi F (2010) Optimization of mechanical properties of thermoplastic starch/clay nanocomposites. *Carbohydr Polym* 79:547–554. doi: 10.1016/j.carbpol.2009.09.001
95. DeLeo C, Pinotti CA, Gonçalves M do C, Velankar S (2011) Preparation and Characterization of Clay Nanocomposites of Plasticized Starch and Polypropylene Polymer Blends. *J Polym Environ* 19:689–697. doi: 10.1007/s10924-011-0311-7
96. Souza AC, Benze R, Ferrão ES, et al (2012) Cassava starch biodegradable films: Influence of glycerol and clay nanoparticles content on tensile and barrier properties and glass transition temperature. *LWT - Food Sci Technol* 46:110–117. doi: 10.1016/j.lwt.2011.10.018
97. Slavutsky AM, Bertuzzi MA, Armada M (2012) Water barrier properties of starch-clay nanocomposite films. *Braz J Food Technol* 15:208–218. doi: 10.1590/S1981-67232012000300004
98. Gao W, Dong H, Hou H, Zhang H (2012) Effects of clays with various hydrophilicities on properties of starch–clay nanocomposites by film blowing. *Carbohydr Polym* 88:321–328. doi: 10.1016/j.carbpol.2011.12.011

99. Katerinopoulou K, Giannakas A, Grigoriadi K, et al (2014) Preparation and characterization of acetylated corn starch-(PVOH)/clay nanocomposite films. *Carbohydr Polym* 102:216–222. doi: 10.1016/j.carbpol.2013.11.030
100. Navarchian AH, Jalalian M, Pirooz M (2015) Characterization of starch/poly(vinyl alcohol)/clay nanocomposite films prepared in twin-screw extruder for food packaging application. *J Plast Film Sheeting* 8756087914568904. doi: 10.1177/8756087914568904
101. Abreu AS, Oliveira M, de Sá A, et al (2015) Antimicrobial nanostructured starch based films for packaging. *Carbohydr Polym* 129:127–134. doi: 10.1016/j.carbpol.2015.04.021

Figure 1. Classification of biodegradable polymers.

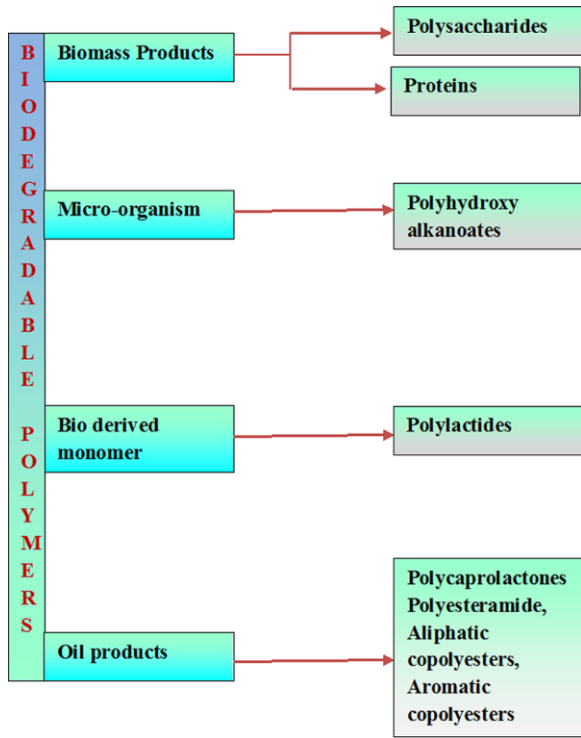


Figure 2 Structure of amylose and amylopectin unit in starch. Reprinted with permission from [73]. Copy right 2015 Elsevier.

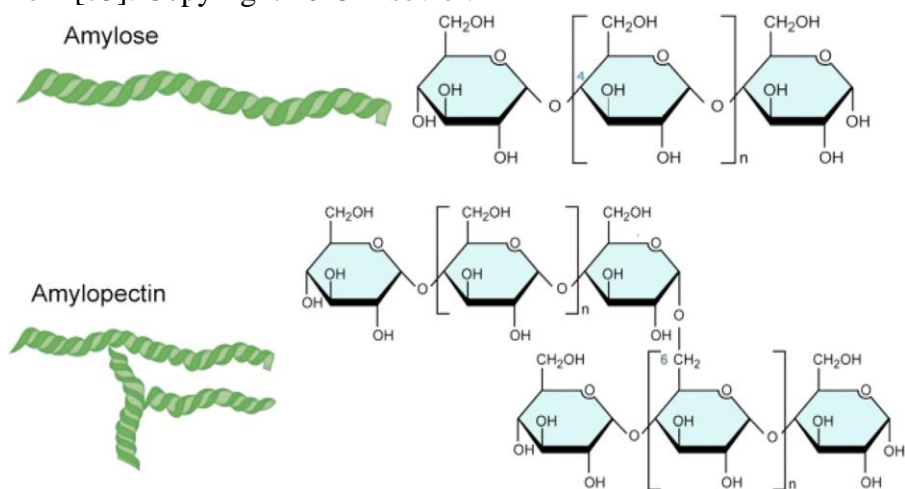


Figure 3 The TEM photographs of PMMT, GMMT, TPS/PMMT and TPS/GMMT. (A) PMMT, (B) GMMT, (C) TPS/PMMT4, (D) TPS/GMMT4. Reprinted with permission [91]. Copy right 2009 Elsevier.

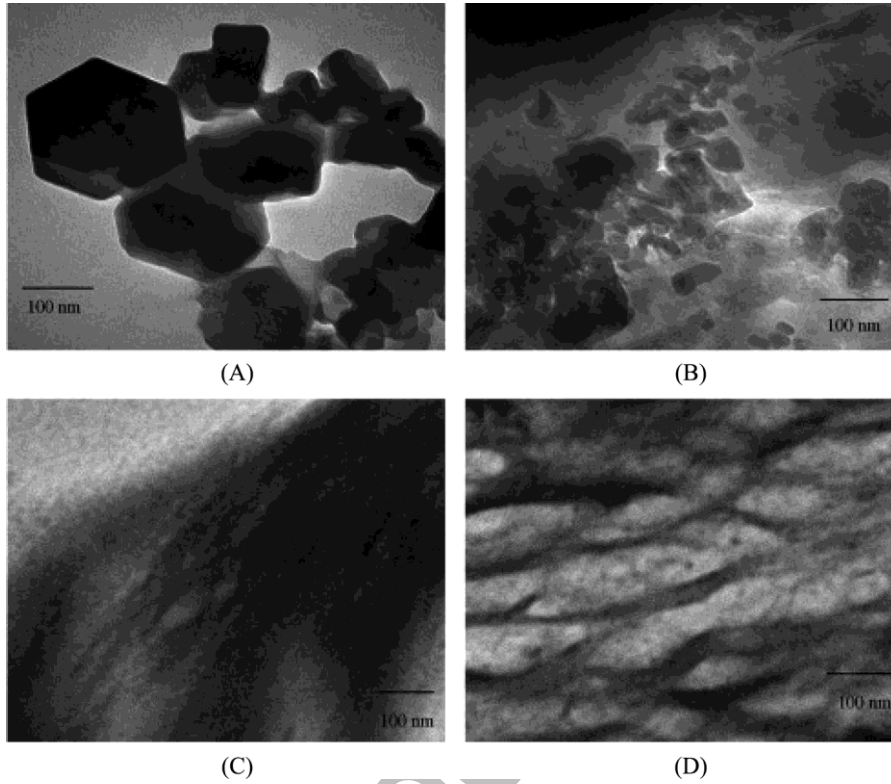
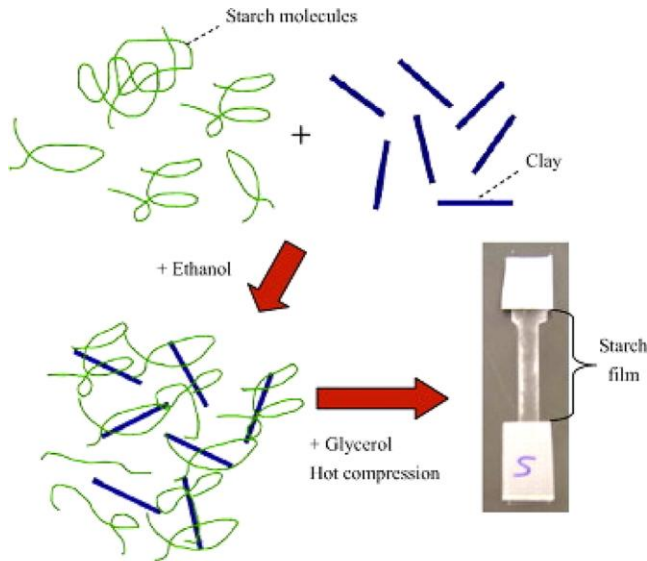
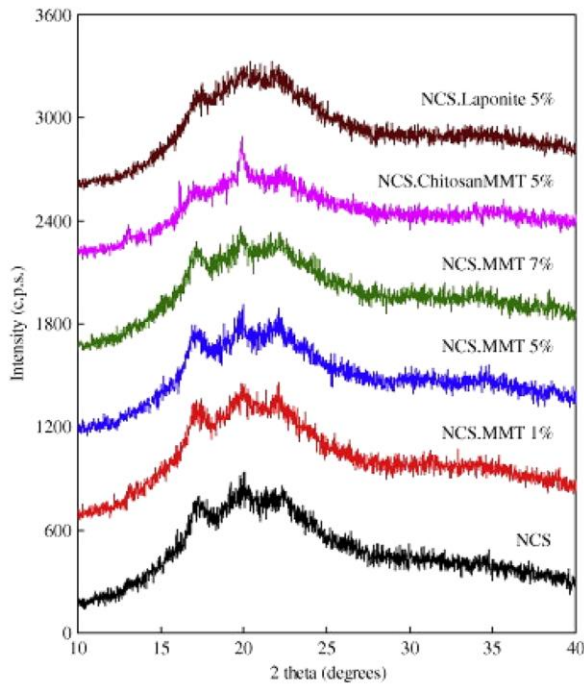


Figure 4. (a) Schematic representation of the synthesis of well-dispersed starch–clay nanocomposites. Reprinted with permission from [92] . Copy right 2010 Elsevier; (b) XRD patterns for starch and various starch–clay nanocomposites containing different amounts of clay. Reprinted with permission from ([92] . Copy right 2010 Elsevier.



(a)



(b)

Figure 5. (a). Nanostructured starch films. Reprinted with permission from [101]. Copy right 2015 Elsevier; **(b)** X-ray diffraction patterns of organo-modified clay C30B, C30B/ST-NC and Ag-NPs/C30B/ST-NC films. Reprinted with permission from [101]. Copy right 2015 Elsevier.

