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Advanced material applications of starch and its derivatives

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Abstract

Starch as a natural polymer has attracted significant interest and is currently used in numerous industrial applications. This is because of its renewability, biodegradability, abundance, and cohesive film-forming properties. Moreover, the hydroxyl (-OH) groups associated with the anhydroglucose units provide it with several modification possibilities. These features resulted in a substantial interest for its use in several advanced functional material applications in addition to the typical consumer plastic applications. The goal of this review is to shed light on the recent advances achieved in the utilization of starch for advanced functional material applications and its derivatives. The review specifically focuses on applications ranging from electronics, drug delivery, pharmaceuticals, antimicrobial materials to structural materials.

Keywords: Starch, Modifications, Esterification, Polymer, Biodegradation, Functional materials

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1. Introduction

Polymers are key materials to mitigate society challenges in the areas of transportation, construction, consumer plastics (e.g. packaging, shopping bags, and cutlery), architectural and industrial coatings, sustainable energy generation, clean water and defense and security. The continuously increasing demand for polymers driven by global population growth, and concerns associated with environmental pollution from solid polymers (e.g. consumer plastics), and the threat of global warming related to the production of polymer feedstock necessitates the development of sustainable and innovative strategies for the polymer industry [1,2]. The use of biomass such as plant fibers, biopolymers produced from natural resources or microorganisms is being explored in numerous applications and across industries [3–5]. While there are some successes in some niche application markets, renewable polymers that are currently produced at a large scale often are costly and have inferior performance compared to their petroleum-derived counterparts.

Among the natural materials, starch is one of the least expensive polysaccharides with a huge potential for solid plastic and other functional polymer applications. Starch, the focus of this work, is a polysaccharide synthesized by plants and found mainly in cereals, roots tubers, fruits and legumes in the range of 25-90% [6,7]. It is a semi-crystalline polymer comprised of about 1,000-2,000,000 anhydroglucose units (AGU) linked by α -1,4 glycosidic bonds[8]. The AGU units in the starch chain have three reactive hydroxyl groups, in most cases one primary and two secondary hydroxyl groups making it amenable to various modification chemistries. Several review articles and books have been published on the physical properties, chemical structures, characteristics, and modification of starch [9–11]. Thus, this review will selectively focus on the

recent progress in the application of starch as a feedstock for advanced and functional material applications of starch.

1.1. Starch as a renewable material feedstock for advanced applications

A starch granule is synthesized via the polymerization of glucose that is produced via photosynthesis of carbon dioxide in plants. It is mainly used as food and finds use in a variety of industrial applications [12]. The major industrial use of starch besides food is as a composition in adhesives and paper binders, textiles, chemical production, a feedstock for fermentation and other industrial products [13]. The interest in starch for use in advanced materials applications is accrued from its widespread geographic distribution from various plants, low cost, and abundance. Starch as a macromolecule is also appealing because of its physical, chemical and functional properties such as ease of water dissolution, water retention properties, gelatinization, pasting behavior when subjected to temperature and ease of modification to optimize functional properties [14]. Unfortunately, the hydrophilic nature of starch alongside its brittleness, retrogradation and thermal degradation has limited its extensive use for industrial polymer applications that require mechanical integrity. Therefore, in most cases, the functional group of starch, i.e -OH group, is modified to mitigate the aforementioned limitations and obtain desirable properties for its success in industrial materials application.

Native starch granule is composed of amylose, a linear glucose chain attached by α -1,4 glucosidase bond, and amylopectin, a branched glucose chain with branching at α -1,6 position[6]. Many studies have shown that the amylose-amylopectin ratio affects the functionality and chemical properties of starch as a biopolymer [8,14]. Table 1 shows various botanical sources of starch and the amylose-amylopectin ratio.

Table 1: Botanical sources of starch and their corresponding amylose/amylopectin ratio, and

Source	Crystallinity (%)	Amylose (%)	Amylopectin (%)	Reference
Rice	38	20-30	80-70	[15,16]
Potato	23-53	23-31	77-69	[16,17]
Cassava	31-59	16-25	84-75	[18,19]
Waxy cassava	N/A	0	100	[18]
Wheat	36-39	30	70	[15,16]
Corn	43-48	28	72	[16,20]
Sorghum	22-28	24-27	76-73	[21,22]

crystallinity.

The structure and composition of starch are responsible for both its physical and chemical properties. The ratio of amylose to amylopectin and the overall structure of starch varies based on the botanical sources, growing climate conditions, geographic location for cultivation and soil type[17]. Starch has A, B and C crystal structures, which is a function of its origin. In general, it has a small granule size and comes in various shapes based on the source[6]. The granule is composed of anhydroglucose units linked by α -1,4 glycosidic bonds to form amylose and amylopectin polymer entities. Amylose is a linear polymer with α -1,4 glycosidic bonds linking the anhydroglucose units with an average molecular weight of 1×10^6 g/mol. It accounts for the amorphous structure in the starch granule. Amylopectin, on the other hand, has a higher molecular weight averaging about 1×10^8 g/mol and linked by short α -1,4 glycosidic bonds with

high branching at the α -1,6 positions that account for the crystallinity in starch[6,23]. The branching of amylopectin polymer creates double helix of approximately 5nm length in the starch granule that aligns in the crystalline region[24]. The crystalline region is represented by double helices as shown in Figure 1.

X-ray diffraction of the macroscopic view of starch under illuminated light showed a positive birefringence indicated by a maltese cross, demonstrating an arrangement of the macromolecular units represented by a helix in the starch morphology, which disappears upon disruption of the starch granule[8]. This interchanging arrangement of amorphous and crystalline lamellae in the starch granule is responsible for the semi-crystalline nature of starch with a crystallinity ranging from 20 to 45% [24].

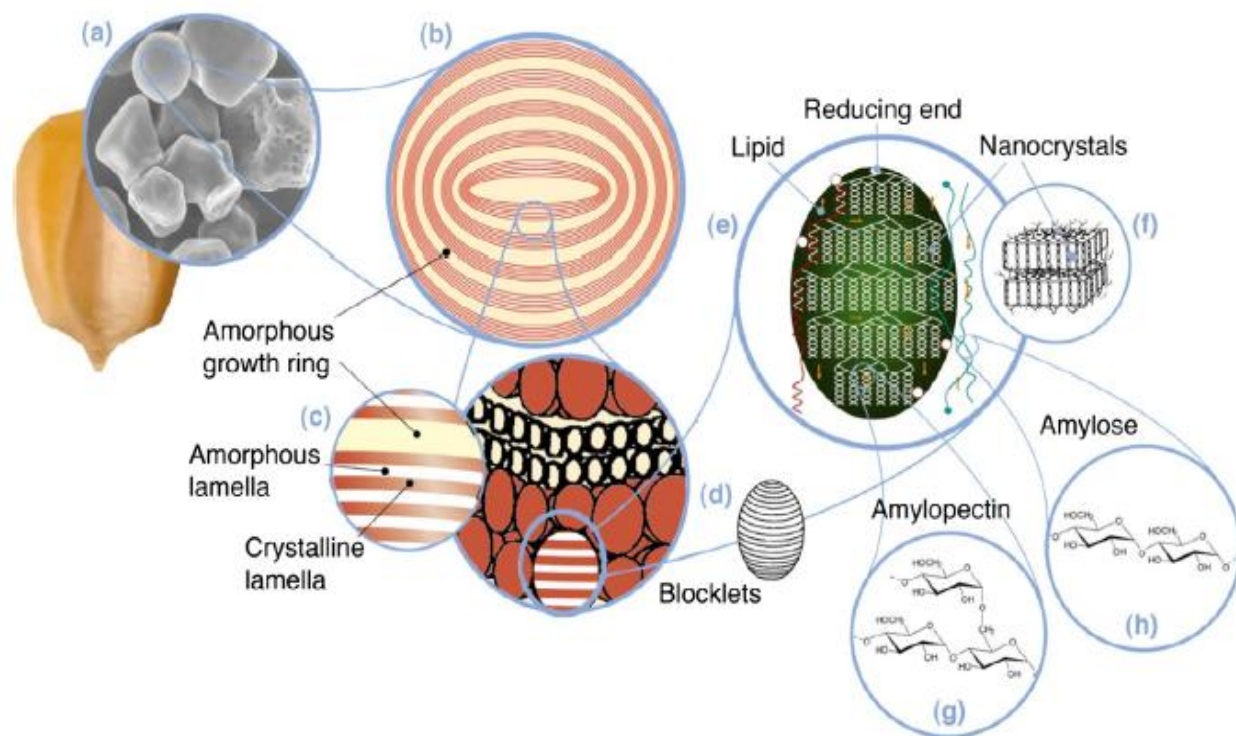


Figure 1. Representation of starch structure (a) Cornstarch granules (30 μm), (b) semicrystalline and amorphous starch growth rings (120–500 nm), (c) crystalline and amorphous lamellae (9 nm), (d) growth rings and blocks internal structures (20–50 nm), (e) Double

helices of amylopectin, (f) starch nanocrystals or called crystalline lamellae when starch nanocrystal is produced via acid hydrolysis, (g) molecular structure of amylopectin (0.1- 1 nm), (h) molecular structure of amylose (0.1–1 nm). Adapted from Le Corre et al [25]. Elsevier copyright © 2014.

Another important component found in starch is phosphorus, a non-carbohydrate component.

Phosphorus exists as monoesters of phosphate and phospholipids. Its presence in the starch granule influences the gel strength, lucidity and solubility depending on the macro-polymer with which it bonds[6].

2. Modifications of starch

Native starch is hydrophilic in nature, insoluble in water at room temperature, and suffers from retrogradation. Furthermore, it cannot be melt-processed as it degrades under relatively low temperature and lacks mechanical integrity. These shortcomings have limited its use for polymer applications requiring mechanical strength and thermal stability, especially in the plastic industry where starch needs to be melt processed in most cases. Also, the poor solubility of starch in cold water limits its potential application as an additive in some applications such as enhanced oil recovery (EOR) and drilling fluid additives. Thus, starch modification is desirable not only to mitigate these challenges but also to bring about other functional properties. Some of the properties that can be achieved via starch modification include thermal stability, hydrophobicity, amphiphilicity, paste clarity, mechanical strength, freeze-thaw stability retrogradation resistances amongst others [26–31]. Several starch modification processes are reported in literature including, physical processes [32,33], chemical modifications [34–37], enzymatic [38–40], and biotechnological approaches [15] or combinations.

3. Starch and its Derivatives for Advanced Functional Applications

3.1. Application of Starch in Self-Healing Polymeric Materials

Hard and brittle polymers and their composites such as thermosets fail catastrophically when cracks develop and grow in their structure. Rapid failure occurs as the crack grows and propagates through the polymer leaving it with the inability to transfer stress efficiently. Elastomers and very low modulus phases can be introduced into the polymer to tackle this problem; they can absorb, deflect or stop these cracks from further propagation when introduced in very small and well dispersed phases[41,42]. However, the inclusion of this type of phase typically deteriorates the mechanical properties of the polymer such as the tensile and flexural strengths and moduli. Mitigating this problem without diminishing the physical properties of the polymer has led to the development of self-healing polymers. Self-healing polymers typically contain hard crosslinked formaldehyde-based microcapsules shells which are well-dispersed within them [43]. This was carried out to allow the microcapsules survive the process of dispersion within the polymer phase without rupture. These microcapsules usually contain highly reactive liquids (healant) such as epoxies, glycidyl methacrylate (GMA) and isocyanates. These liquids, typically monomers can readily react with multiple functional groups on polymer chains because of the presence of reactive groups on their chains. The self-healing mechanism occurs when the microcracks within the polymer propagate, meet and, rupture one or multiple microcapsules containing the healant. The healant flows into the cracks, bridges the gaps and crosslinks over time depending on its surrounding temperature and the type of crosslinking agent present within the polymer phase. Figure 2A shows a schematic of the mechanism by which self-healing polymers repair microcracks.

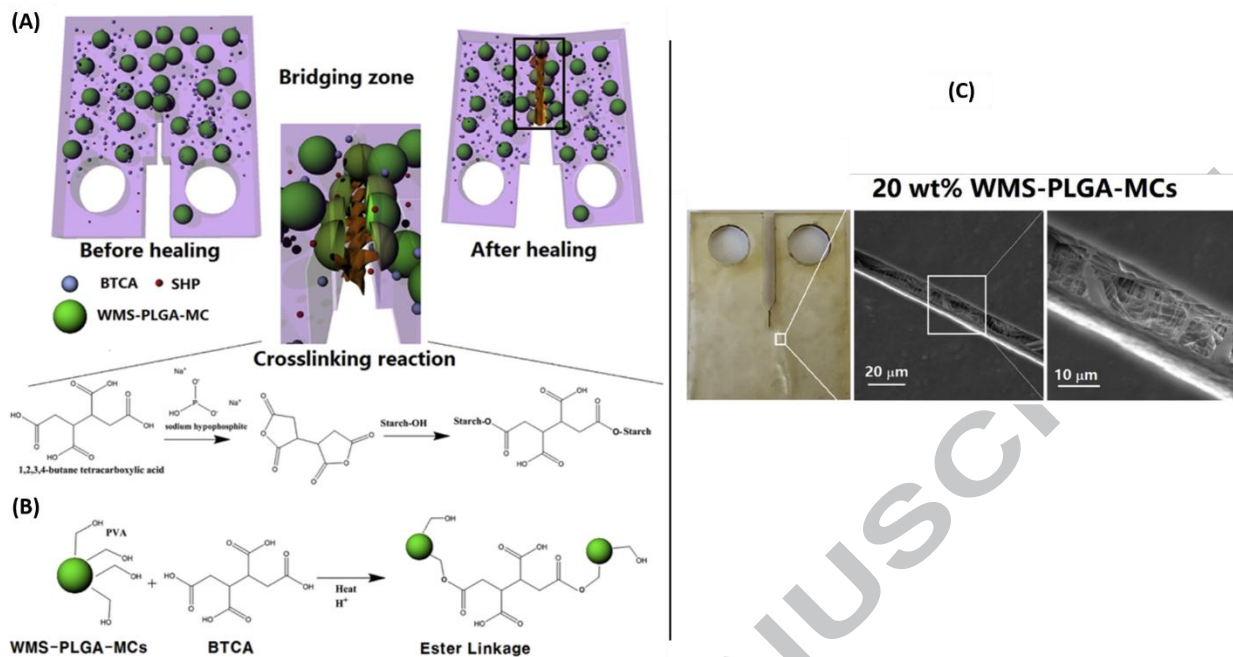


Figure 2. Schematic representing (A) typical mechanism in self-healing polymer with specific reference to start as healant in WMS resin and (B) the esterification reaction occurring between BTCA and WMS. (C) Morphology of WMS resin revealing self-healed WMS resin after fracture with ligaments of crosslinking WMS as healant. Adapted from Kim *et al.*[44]. Elsevier copyright © 2017.

Most self-healing polymers and their healants are petroleum based. However, the utilization of biobased derivatives as healants in polymers have been developed[44,45]. However, only one study has utilized starch as healant in self-healing polymers to the best of our knowledge. Waxy maize starch (WMS) otherwise known as waxy corn starch was used both as the healant and polymer[44]. The WMS was gelatinized to activate the hydroxyl groups on the starch and then encapsulated with poly (d,1-lactide-co-glycolide) (PLGA) by double emulsion solvent evaporation technique. These microcapsules were then incorporated into gelatinized WMS alongside butanetetracarboxylic acid (BTCA) and sodium hypophosphite monohydrate (SHP) as cross-linking agent and catalyst respectively, then cast into a mold to produce sheets, which were cured and cut into test samples. Figure 2A is a representation of the mechanism through which self-healing occurs when the crack ruptures the microcapsule and exposes the WMS. The

catalyst and crosslinking agent were added in excess to ensure good dispersion and contact with the WMS liquid when exposed due to rupture of the microcapsule. The self-heal mechanism occurs through SHP catalyzed esterification reaction between the carboxyl groups of the BTCA in the matrix and the hydroxyl groups of gelatinized starch as represented in the schematic in Figure 2B. The results showed that the healing efficiency increased with increasing microcapsule concentration up to 20 wt. %. It is conceivable that the higher the microcapsule concentration, the greater the probability of the crack rupturing more of these capsules and exposing the healant resulting in better crack bridging. Figure 2C shows the micrograph of a bridged crack after 24 hours of healing of WMS resin with 20 wt.% of microcapsules. The disadvantage to having high concentrations of microcapsules especially in thermoset resins is the potential reduction in the strength of the matrix especially if the interfacial bond between the shell and the matrix is poor as observed in the aforementioned study. This can be alleviated by introducing a compatibilizer to improve the interfacial adhesion between the matrix and capsules. In the aforementioned study, polyvinyl alcohol was used as an interface to improve bonding between the WMS resin and the microcapsule. Micromechanics of polymer reinforcement has shown that spherical particles are most efficient for improving the impact strength or toughness of a polymer while fibrous or platelet particles can drastically improve the strength[41]. Therefore, it will be of great advantage to develop a method of producing microcapsules which are elongated to have an elliptical or fibrous shape. This will not only act as reinforcement for the matrix but will greatly increase the efficiency of the self-healing mechanism as there will be a high probability of rupturing these fibrous capsules due to its greater aspect ratio.

In Table 2, a comparison between close or comparable healing parameters such as healing efficiencies, healant, curing temperatures and mode of evaluation of self-healing polymers are

summarized. Starch-based healant showed a tremendous healing efficiency of 51 and 66 % in comparison to other healants used. Starch being a biodegradable and green material with low cost gives it a great advantage to be further explored as a healant with other polymeric materials as well.

Table 2. Self-healing polymers with similar healing parameters and mode of evaluation.

Self-Healing Material	Mode of Evaluation	Healant	Healing Parameters				Ref
			Healant Concentration (wt. %)	Curing Temperature (C)	Curing Time (h)	Healing Efficiency (%)	
Corn Starch Resin	Tensile Fracture Stress	Gelatinized corn Starch	20	21	24	51	[44]
	Tensile Fracture Toughness		20	21	24	66	
Epoxy	Tensile Fracture Toughness	Dicyclopentadiene	20	25	48	45	[46]
			20	25-30	48	80	
	Tensile Fracture		10	Room temperature	N/A	75	[47]
			40	N/A	48	14	[48]
Poly (dimethyl siloxane) elastomer	Tensile Tear Strength	Vinyl functionalized poly (dimethyl siloxane)/ platinum catalyst	20	N/A	N/A	120	[49]

3.2. Application of Starch in Porous Foam Structures

The binding ability of starch has given rise to its use as a binder, pore former for metallic and ceramic porous foam structures[50–55]. Applications requiring environments with elevated

temperatures and pressures or materials that are inert and biocompatible typically use ceramic or metallic foam structures. These structures have typically been manufactured using other methods such as replication method[56,57] where the ceramic for example fills the empty space of polymer foam structure, is solidified and then the polymeric foam is burned out to reveal the porous ceramic structure. Use of additives as pore formers in coagulating the ceramic particles is another method used in porous ceramic foam structures[58,59]. However, the disadvantage to this is, the ceramic structure is always dependent on the empty structure of the polymeric foam used. Another method used is the agitation of a suspension containing the ceramic particles and foaming agent, which results in closed cell foam generation. A porous structure is formed by the removal of the liquid and sintering of the formed structure. However, these methods have disadvantages as the formation of the pores cannot be controlled. This subsequently results in physical properties and dimensions of a part produced which are dependent on the process. Likewise, dispersion agents and chemicals used in the process are typically expensive and not environmentally friendly.

Starch can provide a lending hand to be used as a pore former in the creation of porous ceramic and metallic structures[53,60]. The manufacturing of the porous structures with starch is done by starch consolidation[50]. The process occurs when a specific amount of starch (the pore former) is added to a specific amount of ceramic slip, which is a suspension of ceramic powder in water (the solids) and heated under constant stirring[61]. The starch granules swell resulting from water intake when the hydroxyl groups are exposed under elevated temperature. This causes water to be drawn from the slip and forces the ceramic powder to consolidate into a solid porous structure. The pore size of this structure is controlled by the swelling of the starch granules; the more it swells, the larger the pore size of the structure is. The swelling or gelation of the starch

also acts as a binder for the newly formed structure. The structure is dried; starch burned out and then sintered. A study investigating the use of native and etherified potato starches for the manufacture of alumina foams was conducted by Lyckfeldt and Ferreira[50]. In this work, the effectiveness of using modified starch (trade name of Trecomex) in comparison to native starch was examined. It was found that gellability and dispersibility of starch in water played a huge role in the production of the porous ceramics structure without critical deformation to its structure. Subsequently, it was also found that the modified starch was better at consolidating the alumina particles. Likewise, it was found that the higher the starch content, the greater the pore size was. A similar result was obtained when 5 and 40 wt. % starch concentrations were used as a pore former in the manufacture of cordierite ceramic foam structures [53].

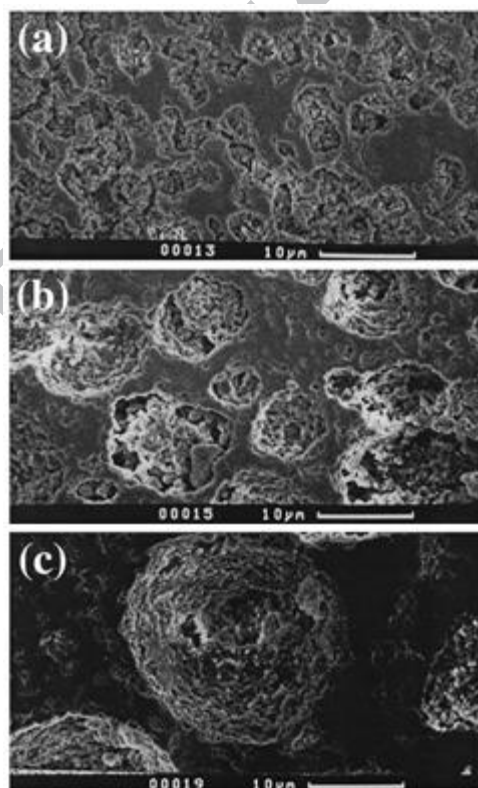


Figure 3. Structures of porous alumina made using a 55% volume fraction of starch that are from (a) rice starch, (b) corn starch, and (c) potato starches. Adapted from Davis *et al.*[51]. Wiley copyright © 2000.

Similarly, the pore structure and size are dependent on the type of starch used[51]. The larger the granular particle size of the starch is, the larger the porosity of the structure. Figure 3 shows the porous structure of alumina porous structures formed using (a) rice, (b) corn and (c) potato starches as pore formers. The granular particle size of these starches increases in the following order; rice < corn < potato. It can be observed that the rice starch showed smaller but somewhat interconnected and co-continuous pore structures (Figure 3a). As the particle size is increased, the pores begin to segregate (Figure 3b) and finally separate when the particle size is the largest (Figure 3c). This suggests that the pore size not only can be engineered by selecting pore formers with desired particle size, but the networking or open porosity of the structure can be controlled as well. The use of starch as pore former has also been applied using the consolidation method in the production of titanium foams with open cell structures[60]. Figure 4 shows the effect of the modified starch (Trecorex) on the storage modulus of the starch, alumina slip mixture (slurry) obtained from rheological analysis. It was observed that at higher temperatures, the slurry containing modified starch exhibited better storage modulus than that containing natural starch. Due to the initial gelation process required to modify the starch, the modified starch is susceptible to gelation at lower temperatures than the natural starch is. Therefore, it swells faster resulting in consolidation and reduced segregation of the alumina particles and higher storage modulus of the slurry at approximately above 55°C.

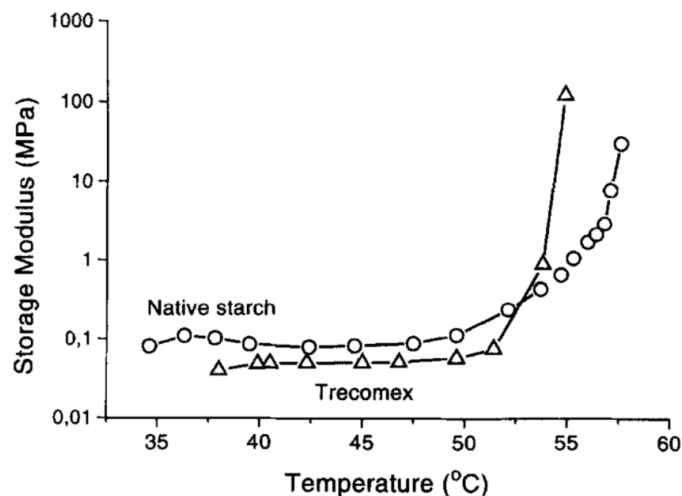


Figure 4. Effect of modified and unmodified starch on the storage modulus of alumina/starch slurry for porous structure manufacture. Adapted from Lyckfeldt *et al.*[50]. Elsevier copyright © 1998.

3.3. Applications of Starch in Water Treatment

Water treatment has been one of the greatest challenges for environmental science because of the ever-increasing amounts and types of contaminants found in it. As technology evolves, the use of various chemicals which are toxic to both humans and the environment is also evolving.

Filtration using micro and nano-membranes have been employed to remove solid contaminants [62,63]. However, soluble contaminants are sometimes notorious to get rid of. Most research has been able to remove these contaminants, however, at the cost of using other chemicals (e.g. polyacrylamide) which could potentially be harmful if trace amounts are left behind. Therefore, a substantial research focus is in place to utilize green or environmentally friendly materials and approaches to decontaminate water. Starch has an abundant potential for use as a substitute for other potentially toxic polymers used in water treatment. This is because starch is non-toxic, sustainable, relatively low cost, and amenable to various chemical modifications that are of interest to water treatment applications. Furthermore, the -OH functional groups on starch

structure could be used as anchor points of contaminant particles[64] in water treatment. Starch as a sorbent or functional material in wastewater treatment has numerous advantages such as availability across the world and renewability, which makes it feasible and attractive economically. In terms of its properties in relation to water, it has an excellent swelling capacity which in turn makes gives it fast kinetics and excellence at removing a wide range of pollutants. Due to its functional groups, it can easily be modified and tailored to target specific pollutants. The gelation characteristics of starch allow it to be soluble in water at elevated temperatures has made it a suitable choice to be used as a dispersant for nanoparticles used in water decontamination[65]. Better dispersion of these nanoparticles will result in improved reactivity to efficiently decontaminate water.

A study by He and Zhao prepared Fe-Pd nanoparticles with and without the use of starch as the dispersing agent or stabilizer for the dechlorination of trichloroethene (TCE) hydrocarbon[65]. Morphological analysis through transmission electron microscopy showed that Fe-Pd nanoparticles without starch were agglomerated and formed a network or dendritic floc with varying densities (Figure 5a). Contrarily, starch-Fe-Pd nanoparticles exhibited remarkable dispersion (Figure 5b).

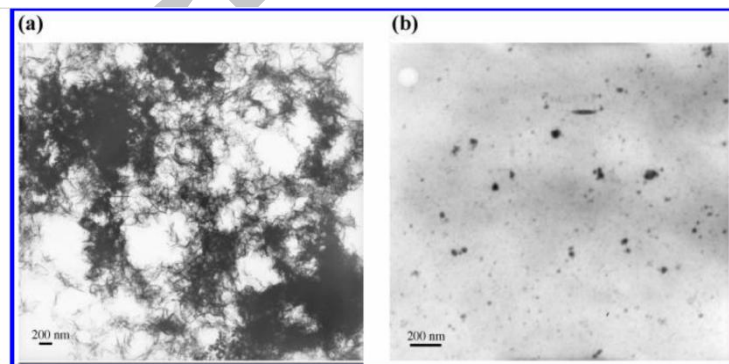


Figure 5. Transmission electron microscopy of Fe-Pd nanoparticles prepared (a) without and (b) with starch as a stabilizing agent. Adapted from He *et al.*[65]. ACS copyright © 2005.

It was found that iron-starch interactions and development of intra-starch Fe clusters contribute a crucial part in dispersing and stabilizing the iron nanoparticles. These nanoparticles were tested for their efficiency in the dechlorination of TCE. The dichlorination rate of starch-Fe-Pd was found to be significantly greater than particles not stabilized with starch. This is because the exposure of the particles to reactivity was far greater when starch was used as a stabilizer in comparison to agglomerated particles, which only reacted with particles that were exposed. To understand the efficiency of starch as a stabilizer, another research has reported similar dichlorination rate but with a concentration of 200 times the amount of Fe particles[66]. A summary of starch derivatives used in the removal of pollutant from water is presented in Table 3. One major drawback of starch used in water decontamination is that the particle size varies with plant source and therefore might perform differently due to difference in surface area.

Table 3. Starch-based materials used in water decontamination.

Material	Contaminant	Ref.
Starch-Fe-Pd	Trichloroethene	[65]
Starch xanthate	Ni ²⁺ , Cu ²⁺ , Cr ³⁺	[67]
carboxymethyl starch	Pb ²⁺ , Cd ²⁺ , Cu ²⁺	[68]
Polymerized starch with epichlorohydrin	Dyes	[69]

3.4. Applications of Starch as Excipient in the Pharmaceutical Industry

An excipient is defined by the international pharmaceutical excipient council (IPEC) as “any substance other than active drug or pro-drug that is included in the manufacturing process or is contained in finished pharmaceutical dosage forms”. Other entities categorize them according to their functions in the final manufacture drug such as binders, disintegrants, diluents, and lubricants [70,71]. The application of starch in the pharmaceutical industry spans from its use as a non-active ingredient, drug delivery to coating and binders in drugs. It is also an important excipient, which the industry uses extensively[71]. This is because of its physical characteristics and properties such as smoothness and ability to be molded, gellability and binding capacity. Moreover, its abundance and availability coupled with low cost, biodegradability, and biocompatibility make it an attractive material to the industry.

The ability of starch to gel has found use as a binding agent in the production of capsules and tablets through the process of wet granulation[72]. Starch is especially suitable in this process as it can act as a dispersing agent to uniformly distribute the drug particles in either high or low concentrations and binds the particles to form loose agglomerates while allowing for easy compression thereafter, to form compacted tablets typically for oral ingestion[73]. It is typically used at low concentrations of about 3 to 20 wt. % with respect to the weight of the compacted tablets[30]. This range of starch concentration is due to the variance in the type and concentrations of other materials used in the formulation as well as parameters in the production of the tablets.

Although starch has been applied as a binder in tablet and capsule production, it also functions as a disintegrant[74]; it aids the breakup capsules shells and tablets for quick release and assimilation of the active components of the drug into the body[71]. Starch is one of the most commonly used disintegrants in the drug industry for tablet and capsule manufacture. The

hydrogen bonds between the starch molecule and the other constituents of the tablet after compaction of the drug help bind the tablet. However, when the drug encounters an aqueous medium (water), the starch granules absorb it; this results in the disruption of hydrogen bonding, swelling of the granules which then elastically deforms[74,75]. This process loosens up the compacted tablet particles, which eventually breaks apart. Figure 6 shows a schematic of the process of drug disintegration into particles, which are then absorbed by the body. Depending on the type of starch used and its position as either indo-, exo- or indo-exo-disintegrants, drug composition and parameter used in the manufacture just to mention a few, the rate of disintegration varies significantly [74].

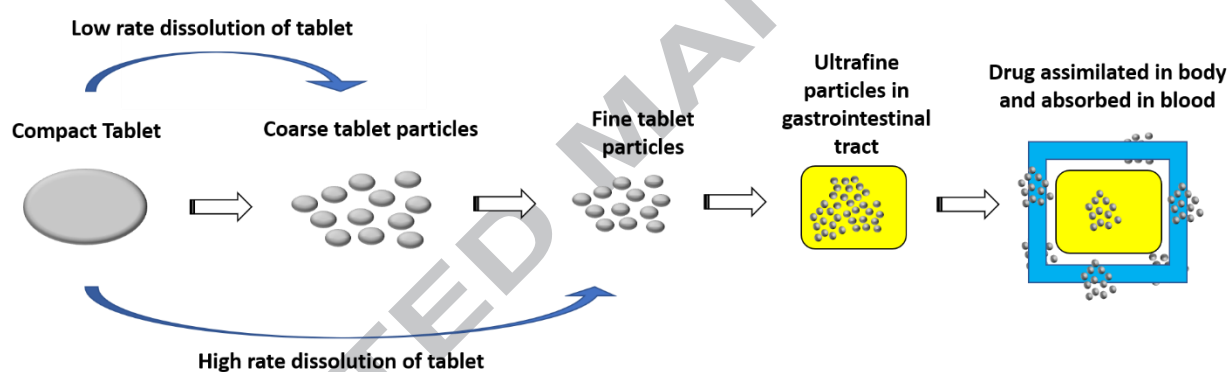


Figure 6. Schematic representation of tablet disintegration and assimilation into the body [70].

Starch is widely used as a disintegrant because it is required at a relatively low concentration ranging from 3-15 wt. % of the total drug weight[30,76]. Native starch in comparison to modified starch, such as re-gelatinized starch performs not as well as modified starch in its binding and disintegrant applications in drugs[71]. This is due to the partial opening of the starch granules after pre-gelatinization, thereby allowing the exposed hydroxyl groups form hydrogen bonds with other starch molecules and active drug particles in the tablet. This results in better

dispersion of the starch within the drug. Hence, bonding is improved and render the disintegration of the drug more efficient.

3.5. Advances in Drug Delivery using Starch

Starch as a green and biocompatible material has currently attracted a substantial interest as a potential drug delivery agent as well as in controlling the rate of active drug release over periods of time. The drug release over time of tablets can be controlled through the modification of the dual functional native starch used as binder and disintegrant. Odeku *et al* [77–81] studied various starches from various sources in tablet manufacture and found that the rate of disintegration, which is also related to the rate of active drug component release was greatly affected by the source of the starch and the modification type done to the native starches. Depending on the type of modification carried out to starches such as acid modified, pre-gelatinized, freeze-dried, crosslinked and hydroxypropylation, the disintegration and binding properties are significantly affected, which consequently affects the rate of drug release. Similarly, the source of the starch is also a great influencing factor of these properties as well. Therefore, it is important that the right source of starch and modification be chosen to target specific drug release.

Alexiou *et al*[82] conducted a study to explore the biocompatibility and reactivity of starch as a carrier for targeting cancer cells. In this study, iron oxide nanoparticles were sized with modified starch containing phosphate groups, which were then infused with mitoxantrone as a chemotherapeutic drug [82]. It was shown that by applying a magnetic field over the cancer tissues in the subject, these nanoparticles concentrate in these areas and destroy the cancer cells by penetrating them.

Ahmad *et al*[83,84] developed a novel method of drug delivery in the gastrointestinal tract (GIT) using bioadhesive microspheres (BAM) synthesized from rice starch by double emulsion evaporation method. In this study, BAM was used as a carrier for metronidazole for colon and intestinal disease treatment. It was shown that these microspheres were able to withstand microbial degradation and hydrolysis from enzymes, acids and alkalis, thereby resulting in slow drug release for a prolonged period. It was also suggested that this novel application of starch can be used as a carrier for other types of effective drugs to combat gastrointestinal tract infections. Using the same rice starch but modified by carboxylation and oxidation, Ahmad *et al*[85] studied the drug release rate of tablets containing metronidazole. It was found that the modified starches were effective in the release rate and varied depending on what environment the tablet was in within the GIT.

The thermo-sensitivity of starch derivatives has recently been geared towards drug delivery[86]. This novel research is based on previous technology where thermo-sensitive polymers have been used in drug delivery [87]. The swelling and expansion, which occur when starch is exposed to moisture at elevated temperatures have been used to control the release of drugs. This mechanism was applied to corn where it was degraded using acid to expose functional groups in the starch granules[86]. This treated starch was then reacted with butyl glycidyl ether under controlled parameters to yield micelles of 2-hydroxy-3-butoxypropyl starch polymers.

Prednisone as the choice of drug was then loaded into the modified starch through a dialysis process. The results showed that the modified starch carrying hydrophilic alkyl groups can form micelles and the lower critical solution temperatures (LCST) of this starch was a function of the degree of molar substitution (MS) of butyl glycidyl ether to the anhydroglucose units of the starch molecules. By doubling the MS from 0.32, the LCST was decreased from 32.5 to 4 °C.

This indicates that the micelles can be designed to swell and control the rate of drug release at different temperatures. With the LCST of the modified starch micelles determined to be 32.5 °C, they were tested for their drug release in distilled water at 20 and 40 °C. It was found that 38 % of the drug was released at 20 °C while 90 % was released at 40 °C. In both cases, the duration of the study was 100 h. At temperatures above the LCST, the micelle structure was less stable, resulted in a failure to confine the drug, and therefore caused it to leach out of the structure. Starch in combination with polymers for porous media and drug infusion is another area that has also been investigated. Microcapsules, where starch is utilized in drug delivery has also been investigated. These applications of starch in drug delivery systems have been summarized in Table 4.

Table 4. Modified starch and their application towards drug delivery systems

Material	Delivery Method	Preparation Technique	Result/Summary	Ref.
Cornstarch-Polycaprolactone blend	Porous microparticles	Emulsion solvent extraction/evaporation	This study was able to produce microparticles ranging in sizes from 5 to 900 μm with both smooth and porous surface morphologies. In-vitro studies also showed that there was a steady release of the drug of choice over a 30-day period, indicating its potential as a carrier for other active drug ingredients	[88]
Sweet potato starch	Microparticles	Spray-drying of gelatinized starch	This studied produced heterogeneously shaped particles which showed a drug release sustainability of over 6 h. it also showed that the concentration of starch used in the production of the particles, as well as that of the model drug, affect the release	[89]

			rate.	
Corn and potato starches	Hydrogel	Isostatic ultra-high pressure	The result from this study showed that corn starch-based hydrogel carrier exhibited sustained drug release while potato starch-based hydrogel exhibited fast drug release. This study showed that the source of the starch could significantly affect the developed drug carrier properties.	[90]
Hydrolyzed potato starch	Microspheres	Single emulsion crosslinking	This study produced microspheres with diameters ranging from 3 to 540 μm . Particle size was shown to be dependent on the crosslinking reaction while the release of the drug was rapid within the first 2 h regardless of the medium used.	[91]
Glutinous rice starch and polyvinyl alcohol blend	Microfibers	Electrospinning	Changing the ratio of starch to PVA ratio showed an effect on the type of fibers produced; either beaded or smooth cylindrical fiber. The study also showed that the fibers had a high water-soluble index, which was excellent to be used as a drug carrier. Drug release test showed that the initial release was from the PVA phase while the sustained release was from the starch phase. This indicates that a quick and sustained dose can be applied when using a model drug.	[92]
Crosslinked starch	Mucoadhesive starch nanoparticles		The results showed that the nanoparticles were effective in rapid drug release and dependent on the particle size. Likewise, the degree of crosslinking was observed to have an effect on the drug release rate as well.	[93]

3.6. Antimicrobial films and coatings based on starch

The proliferation of antibiotics resistant bacteria has posed a substantial demand for innovative strategies to fight pathogenic bacterial infection in the health and personal care as well as food contamination. Polymers that have antimicrobial properties represent a valuable alternative to

conventional antibiotics and is currently gaining interest in coatings, personal care and active food packaging, and biomedical applications. Typical antimicrobial agents used with polymers are organic or inorganic acids, metals, alcohols ammonium compounds or amines [94]. However, due to the low molecular weight of these antimicrobial agents, their retention capacity has been reported to be poor causing them to leach out when applied directly to a substrate or polymer system, thereby inhibiting their antimicrobial performance. The interest in starch as an antimicrobial agent carrier is accrued from its film-forming properties, and high molecular weight. The use of such high molecular weight polymer as a carrier of antimicrobial polymer eliminates the problem of leaching via entanglement and other interactions with the baseline plastic making polymer [95,96]. In addition, starch is economical, environmentally friendly, and non-toxic making it appealing in food packaging and biomedical applications. Typically, the antimicrobial agent is covalently bonded to starch via a synthetic strategy to improve its retention in polymers.

Guan *et al* [96] synthesized antimicrobial modified starch by covalently bonding polyhexamethylene guanidine hydrochloride (PHGH) with potato starch through a coupling reaction using glycerol diglycidyl ether (GDE) to improve its adsorption on cellulose fibers. A shaking flask method was used to evaluate the biocidal activity against *E. coli* and *S. aureus* while atomic force microscopy was used to monitor the antimicrobial mechanism. Their results revealed that 1 wt.% PHGH modified starch in cellulose fibers inhibited the growth of the studied bacteria by almost 100 % [96]. A similar study carried out by Ziaee *et al* [95] using modified starch containing 12 wt.% PHGH with as low as 20 mg/g PHGH modified starch dosage on cellulose fibers revealed excellent antimicrobial activities against *E. coli* bacteria as indicated by the collapse of bacteria membrane investigated by AFM and the growth of *C.*

globosum fungi investigated by SEM. In this studies, introducing the modified starch in fibers increased the tensile index and decreased the tear index simultaneously [95]. Several other authors have also researched and reported positive antimicrobial outcomes by using guanidine hydrochloride based modified starch [97,98].

Pelissari *et al* prepared a film from plasticized starch-chitosan modified with oregano essential oil (OEO) at concentrations of 0, 0.1, 0.5 and 1 % and investigated the antimicrobial properties against *Bacillus cereus*, *Escherichia coli*, *Samonella enteritidis* and *Staphylococcus aureus* using the disk inhibition zone method. From their results, although a higher inhibition halo was observed for *B. cereus* and *S. aureus* (gram positive) and a smaller inhibition halo for *S. enteritidis* and *E. coli* (gram negative), all OEO modified films exhibited inhibition zones, which increased with an increase in OEO concentration. The presence of OEO in starch films not only improved the biocidal activity but also improved hydrophobicity and water vapor barrier properties [99].

Shen *et al* plasticized potato starch and prepared antimicrobial starch films modified by incorporating potassium sorbate or chitosan at concentrations of 0, 5, 10, 15 g/100 g starch and observed the biocidal activity of modified films against *E. coli* and *S. aureus*. Films prepared with 10% or less potassium sorbate could not suppress the growth of *E.coli* and showed no inhibition zones. They suggested an interaction between the hydroxyl group in starch and the carboxyl group in potassium sorbate limited the release of potassium sorbate responsible for inhibiting the growth of bacteria from the film; hence limiting the biocidal activity. On the other hand, significant inhibition zones were observed when the concentration was increased to 15 % resulting from the release of sorbic acid from the starch films. The films prepared with chitosan revealed inhibition zones at 5 % with an increase in the inhibition zone diameter as the

concentration increased to 15 %. Potassium sorbate starch films tested against *S. aureus* revealed no inhibitory zones as compared to chitosan-starch films which inhibited the growth of *S. aureus* at 10 % concentration; with no change in activity with an increase in concentration. The films that revealed inhibition zones in both cases showed no contamination, which suggests that these antimicrobial agents inhibited the growth of other microorganisms as well. In addition to the biocidal activity, the presence of these antimicrobial agents impacted the mechanical properties, water vapor and oxygen permeability, and solubility of films [100]. Other examples of starch utilization in antimicrobial polymer applications are presented in Table 5.

Table 5: Antimicrobial modified starch and its activities.

Starch Source	Antimicrobial Agent	Concentration	Microorganism	Remarks	Reference
Potato	PHGH	1 %	<i>E. coli</i> <i>S. aureus</i>	100 % inhibition	[96]
		12 %	<i>E. coli</i> <i>C. globosum</i>	Excellent antimicrobial activities	[95]
Cassava	Chitostan-oregano	0.1, 0.5, 1 %	<i>B. cereus</i> , <i>E. coli</i> , <i>S. enteridites</i> , and <i>S. aureus</i>	Increased biocidal activity against gram positive than gram negative bacteria	[99]
Sweet Potato	Potassium Sorbate	5, 10, 15 %	<i>E. coli</i>	No inhibition zones at ≤ 10 %	[100]

			<i>S. aureus</i>	No inhibition zones	
	Chitostan	5, 10, 15 %	<i>E. coli</i>	Inhibition began at 5 % concentration; increased with concentration	
			<i>S. aureus</i>	Inhibition at 10 %, no increase with concentration	
Tapioca	Chitostan	1 %	<i>Lactobacillus spp</i>	Low effectiveness	[101]
			<i>Zygosaccharomyces bailii</i>	Effective	
	Chitostan- Potassium sorbate	3 %	<i>Zygosaccharomyces bailii</i>		
			<i>Lactobacillus spp</i>	No inhibition	
Wheat	Chitostan	Various	<i>B. subtilis</i> <i>E. coli</i>	Low inhibition	[102]
	Chitostan- lauric acid	8 %	<i>B. subtilis</i> <i>E. coli</i>	Efficient inhibitory effect	
Potato	Guanidine	4,8,12,16 mol	<i>E. coli</i>	Excellent antimicrobial	[98]

starch	hydrochloride	% compared to starch	<i>S. aureus</i>	properties	
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3.5. Other advanced applications of starch and its derivative materials

Technological advances and research have certainly focused on the use of starch in various applications such as electronics, photonics, energy, sensors and superhydrophobic surfaces. The property and ability for the starch to form thin films when gelatinized and cast on a substrate have lent itself as a moisture barrier in the application of superhydrophobic papers. In a study by Chen *et al*, a superhydrophobic paper was fabricated by the casting of two layers of solutions on the surface of paper [103]. The first layer comprised of a gelatinized starch composite containing enzyme, sizing agent, crosslinker and aluminum sulfate as a pH adjuster and was rolled on while the second layer was a suspension of hexamethyldisilazane treated silica nanoparticles (HMDS-SiNPs) in ethanol. This layer was immediately sprayed on after the application of the gelatinized starch and allowed for the ethanol to evaporate. This allowed for the bonding of the HMDS-SiNPs to the starch layer while it was curing. Results from the contact angle test showed that the treated paper was superhydrophobic with a contact angle of 162 degrees as shown in figure 7a. The presence of the HMDS-SiNPs on the surface acted to repel the water molecules. In a submersion test, both treat papers with and without the first layer of gelatinized starch were completely submerged in water for a period of 2 mins. The paper without the starch layer was completely soaked and allowed water to penetrate through its fibers. However, the paper with both layers treated was dry after the 2 mins water immersion. For this, it was suggested that the thin film formed from the crosslinked and gelatinized starch clogged the porous structure of the paper fibers and prevented water from penetrating through it. Other significant improvements

noticed were increased mechanical durability of the treated paper. Likewise, the visual appearance of the paper after treatment was not affected since very thin layers were applied. It can be observed that the tailoring of starch with other materials can provide several interesting attributes with numerous applications; one such feature is hydrophobicity of starch that is inherently hydrophilic.

Starch has been shown to have comparatively good optical properties, which can be channeled for use in various applications. The application of starch as a substrate in photonics in comparison to other biopolymer substrates has been investigated by Cyprych *et al* [104] and shown to have greater photostability due to its low oxygen permeability. In this study, starch was gelatinized using water and then doped with rhodamine 6G water solution, which acted as a light amplification medium. This mixture was casted on a glass substrate and allowed to air dry, forming a layer of rhodamine 6G doped modified starch. When the doped starch was photoexcited, a generation of random lasing effects was observed due to the formation of a random roughness of the starch granules deposited on the substrate. In comparison to other biomaterials such as DNA, and proteins, starch could exhibit better photonic properties. Figure 7b shows a schematic of the mechanism of random lasing due to the random formation of starch granules on a glass substrate. This work showed that starch has the potential to be used in photonic applications such as light emitting diodes and color imaging. With further research and development, the future of and applications of starch-based phonic materials seems promising.

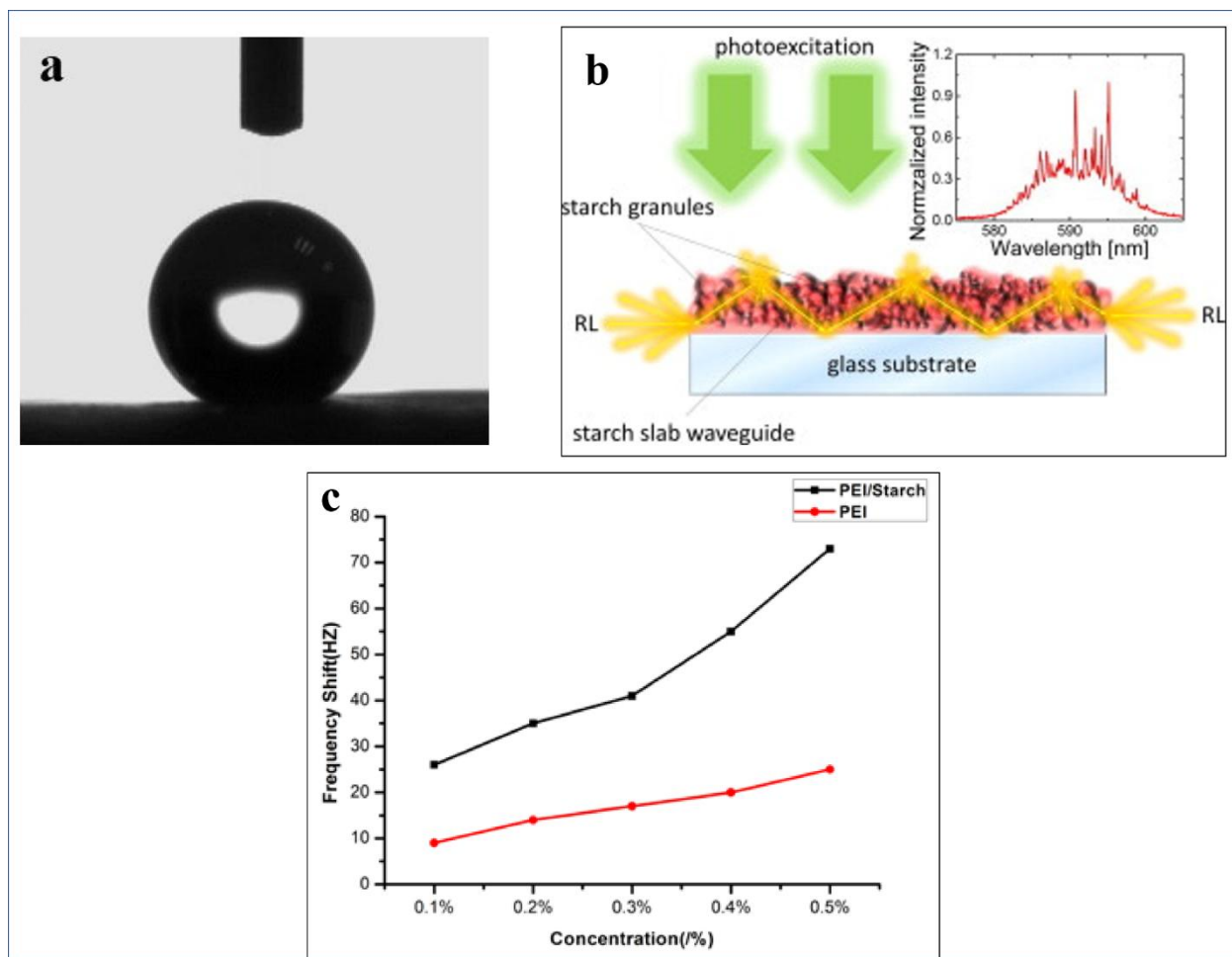


Figure 7. (a) Contact angle test of superhydrophobic paper modified with starch composites. Adapted with permission [103]. Copyright 2017. Elsevier, (b) Schematic representation of random lasing of modified starch on glass substrate after photoexcitation is applied. Adapted with permission [104]. Copyright 2017. Elsevier, and (c) The effect of frequency changes of PEI and PEI/starch film sensors materials as a function of carbon dioxide concentration. Adapted with permission [105]. Copyright 2011. Elsevier.

With the rate of carbon dioxide emissions from our ever-growing industries around the world, we have seen great significance in climate change. One of the areas starch has been used is in research and development of sensors for carbon dioxide. In a study by Sun *et al* [105], polyethylenimine (PEI) and polyethylenimine-starch composite films were spin coated on quartz crystal microbalance sensors. Carbon dioxide and nitrogen gases were pumped alternatively and the sensitivity through frequency changes were observed. It was noted that the PEI/starch

composite exhibited significantly higher sensitivity to the carbon dioxide. Figure 7c shows the effect of carbon dioxide gas concentration on the frequency changes of both PEI and PEI/starch films. Both films showed an increase with increasing carbon dioxide concentrations while the PEI/starch film showed significantly greater frequency changes in comparison to that of the PEI film. It was postulated that the greater sensitivity to carbon dioxide was due to the more protonation of the amino groups within the PEI polymer thereby increasing recognition of carbon dioxide at the polymer layer. The mechanism through which this occurred was deduced to come from the presence of starch attracting moisture to the surface of the film and subsequently interacting with carbon dioxide to form carbonates and bicarbonate ions. This study shows that starch is a versatile material and with fundamental understanding of its properties, it can be geared towards specific applications.

4. Outlooks, Prospects and Conclusions

The environmental concerns from the utilization of non-sustainable, non-biodegradable and toxic feedstock in industrial applications have created an increased interest for the need to research and develop biomaterials with starch being a sort after and potential candidate because of the many benefits it brings. The environmentally friendliness and ease of chemical modification such as gelatinization and blending of starch with other materials such as polymers have been shown to produce desirable properties suited to specific end use. By varying the type, level and degree of modification in modified starch, the physicochemical properties of the final material based on starch can be varied. Utilization of starch as healant in self-healing thermoset resins have shown to be a viable alternative material to currently used highly reactive and toxic chemicals [44]. Drug delivery systems require carriers and materials that can easily be modified and used as carriers for dosage of active drugs at specific sites. Starch has shown great promise for use in

drug delivery system especially because of its biocompatibility and degradability within the subject after effective release of the drug. Likewise, it is less-expensive and readily found across the globe. Properties of starch such as bindability, and gel-ability has found many uses in the pharmaceutical industry to act as disintegrants, binders, dispersants and lubricants. They have also found utilization in the production of porous metallic and ceramic media for applications such as filtration and tissue engineering. With the world focused on moving towards sustainability, starch has found itself as one of the for front runners in the development of functional materials for advanced applications. While starch can complement efforts towards the development of renewable polymers, perceived competition with food production could limit its extensive utilization in commodity applications. However, its use in functional and advanced material application is expected to attract more attention.

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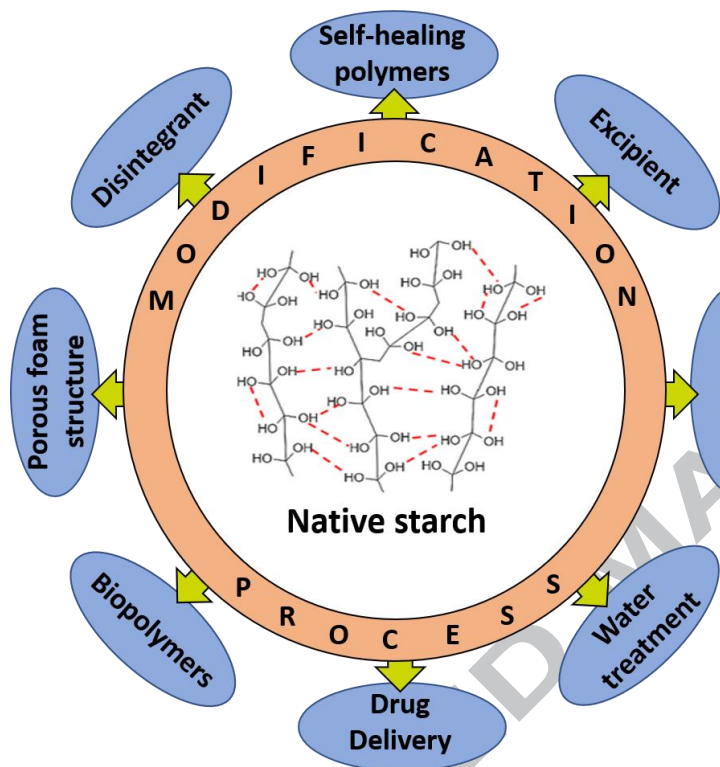
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Graphical abstract



Highlights

- Starch has desirable functional properties that can be modified and geared towards advanced applications.
- Utilization of starch in advanced materials application is desirable due to its low cost, biodegradability, biocompatibility ease of modification.
- Starch has tremendous applications in the medical field due to its biocompatibility.
- Starch is a readily available material which has numerous applications up on modifications.

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