

## Chitosan-Based Polymer Blends: Current Status and Applications

<sup>1</sup>Esam Abdulkader El-Hefian\*, <sup>2</sup>Mohamed Mahmoud Nasef and <sup>3</sup>Abdul Hamid Yahaya

<sup>1</sup>*Department of Chemistry, Faculty of Science, University of Zawia, Az Zāwīyah, Libya.*

<sup>2</sup>*Institute of Hydrogen Economy, Universiti Teknologi Malaysi, Jalan Semarak,  
54100 Kuala Lumpur, Malaysia.*

<sup>3</sup>*Department of Chemistry, University of Malaya, 50603 Kuala Lumpur, Malaysia.  
eelhefian@yahoo.com\**

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**Summary:** This paper reviews the latest developments in chitosan-based blends and their potential applications in various fields. Various blends together with other derivatives, such as composites and graft copolymers, have been developed to overcome chitosan's disadvantages, including poor mechanical properties and to improve its functionality towards specific applications. The progress made in blending chitosan with synthetic and natural polymers is presented. The versatility and unique characteristics, such as hydrophilicity, film-forming ability, biodegradability, biocompatibility, antibacterial activity and non-toxicity of chitosan has contributed to the successful development of various blends for medical, pharmaceutical, agricultural and environmental applications.

Keywords: review, chitosan, natural polymer, blend, application.

### Introduction

Natural polymers have attracted an increasing attention over the past two decades, mainly due to their abundance and low cost in addition to environmental concerns, and the anticipated depletion of petroleum resources. This has led to a growing interest in developing chemical and biochemical processes to acquire and modify natural polymers, and to utilise their useful inherent properties in a wide range of applications of industrial interests in different fields [1, 2].

Among the natural polymers, chitosan occupies a special position due to its abundance, versatility, facile modification and unique properties including biodegradability [3], biocompatibility [4, 5], non-toxicity [6] and anti-bacterial [7], as well as, hydrophilicity [8]. This has made chitosan a very useful compound in a wide range of applications in medical, pharmaceutical, chemical, agricultural and environmental fields.

To improve chitosan's properties and further diversify its applications, various strategies have been adopted. This includes: 1) crosslinking [9–11], 2) graft copolymerisation [12–16], 3) complexation [17–23], 4) chemical modifications [24, 25] and blending [26–29]. In particular, modification of chitosan by means of blending is an attractive method that has been extensively used for imparting new desirable characteristics to chitosan [30–34]. This is mainly due to its simplicity, availability of a wide

range of synthetic and natural polymers for blending and effectiveness for practical utilisation.

Recently a number of review articles on chitosan derivatives (crosslinked, graft copolymers, complexes and composites), properties and potential applications in biomedical, pharmaceutical, veterinary medicine, and environmental applications have been reported [35–45]. However, a specific review dedicated to chitosan blends and their potential applications has not been published despite the considerable amount of publications in this field.

This article reviews chitosan blends and their various aspects including its blending methods with natural and synthetic polymers. Moreover, utilization of chitosan blends in various fields ranging from biomedical to environmental applications are also presented with some focus on fast growing ones. The scope of this review also covers basic fundamentals of chitosan aspects including structure, preparation and applications.

### *Chemical Structure and Preparation of Chitosan*

Chitosan, 1 → 4 linked 2-amino-2-deoxy-β-D-glucopyranose, is the deacetylated derivative of chitin [46–49], the most abundant natural polymer (polysaccharide) on earth after cellulose [50–52]. The most important sources of chitin today are crustaceans [53–56], such as shrimps, squids and crabs. Chitin and chitosan are similar to cellulose

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\*To whom all correspondence should be addressed.

with respect to their physico-chemical properties and functions caused by similarity in molecular structure. Figure 1 shows the molecular structure of chitin, chitosan and cellulose. The only difference among the three polysaccharides is the acetamide group on the C-2 position of chitin and the amine group in chitosan that is replacing the hydroxyl group found in cellulose.

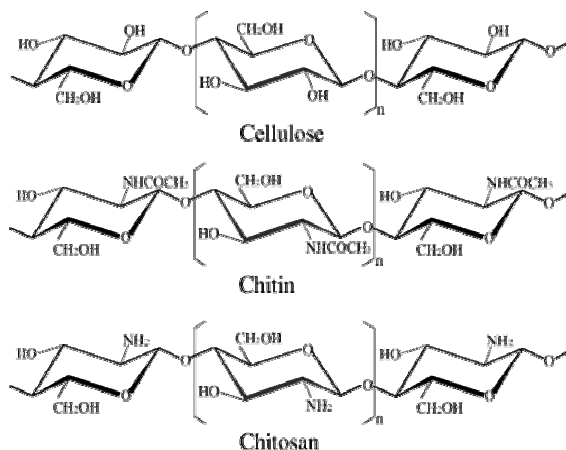


Fig. 1: Chemical structure of cellulose, chitin and chitosan.

Chitin can be completely acetylated, completely deacetylated and partially deacetylated. However, a complete deacetylation of chitin is rarely achieved. Chitosan is often described in terms of the average molecular weight and the degree of deacetylation (DD). In general, chitin with a degree of deacetylation of 70% or above is considered as chitosan [57]. Chitin and chitosan are both prepared using the common process illustrated in Figure 2 [58]. The raw chitosan is dissolved in aqueous 2% w/v acetic acid. Then, the insoluble material is filtered giving a clear supernatant solution, which is neutralised with NaOH solution resulting in a purified sample of chitosan as a white precipitate. Further purification may be necessary to prepare medical and pharmaceutical-grades of chitosan.

Chitosan is commercially available in various countries. The majority of its commercial samples are available with DD ranges between 70 to 90% and always less than 95% [59]. Tolaimate *et al.* [60] have reported that chitosan with a DD higher than 95% may be obtained via further deacetylation steps. However, this may result in partial depolymerisation as well as increase the cost of the preparation. On the other hand, the DD can be lowered by reacetylation [46].

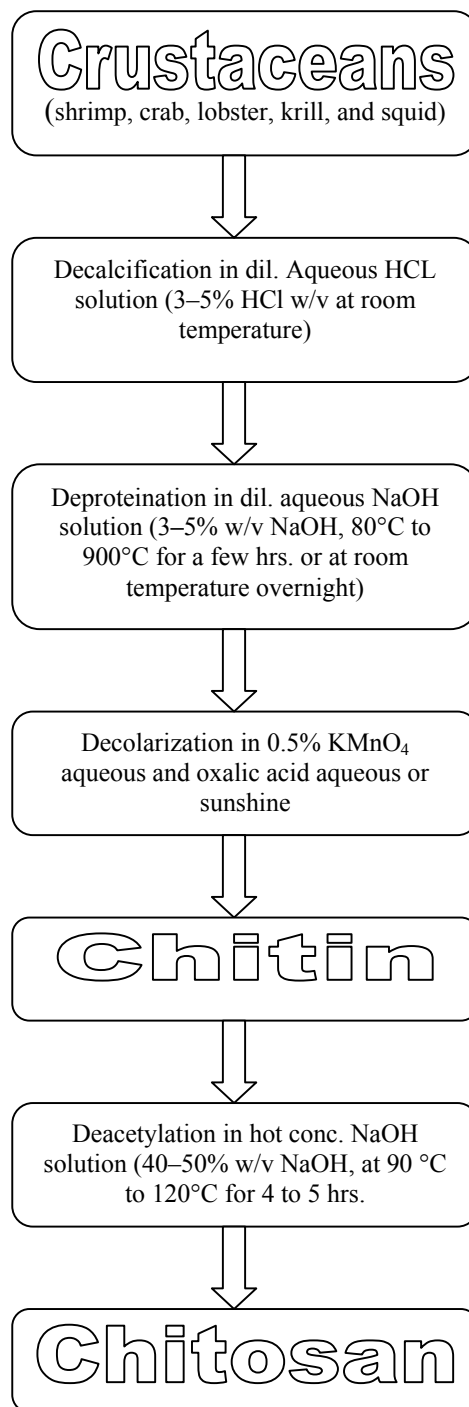


Fig. 2: Common process for preparation of chitin and chitosan.

#### Properties of Chitin and Chitosan

Chitosan has become the subject of research due to its unique properties and ease of modification [61-63]. The physical [61], chemical [64] and

biological properties [65, 66] of chitin and chitosan depend on two parameters: degree of deacetylation (DD) and molecular weight distribution [67], which are dictated by the chitin sources and the method of preparation [68]. In fact, the DD of chitosan influences not only its physico-chemical characteristics, but also its biodegradability [69, 70]. In addition, the DD is also reported to have an impact on the performance of chitosan in many of its applications [71, 72].

#### *Physical Properties*

Chitosan exists in a form of white, yellowish flakes, which can be converted to bead or powders. The DD also plays a vital role on the molecular weight of chitosan. In particular, the lower the DD the higher the molecular weight, which provides higher chemical stability and mechanical strength. The average molecular weight of chitosan is approximately  $1.2 \times 10^5 \text{ g. mol}^{-1}$  [73].

Chitin and chitosan are amorphous solid biopolymers that almost insoluble in water. This is most likely due to presence of strong intermolecular hydrogen bonds, which are formed between the molecular chains of chitosan. Therefore, the solubility of chitosan in water is controlled by the balance established between the electrostatic repulsion forces caused by the protonated amine functional groups and the hydrogen bonds resulting from the presence the free amino groups [74].

Chitin is insoluble in most organic solvents. Nevertheless, it dissolves in corrosive chemicals such as *N*-dimethylacetamide (DMAC) containing lithium chloride. On the contrary, chitosan is soluble in aqueous organic acid solutions, such as formic acid and acetic acid at a pH below 6, and becomes a cationic polymer solution due to the protonation of the amino groups available in its molecular structure. However, chitosan hardly dissolves in pure acetic acid. In fact, concentrated acetic acid solutions at high temperatures may cause the depolymerisation of chitosan. The solubility of chitosan in dilute acids depends on the DD in the molecular chains of chitosan. Consequently, this property can be used to distinguish between chitin and chitosan [75]. A DD of 85% has to be attained in solid chitosan so that its desired solubility can be achieved. Furthermore, the properties of chitosan solutions depend not only on its average DD but also on the distribution of the acetyl groups along the molecular chains [76, 77] and the acid concentration as well as the type of acid [78].

Chitosan also dissolves in hydrochloric acid under certain conditions. However, it does not dissolve in sulfuric acid because of the formation of insoluble chitosan sulfate [79]. Aqueous solutions of acids such as phosphoric, citric and sebacic acids are poor solvents for chitosan [80]. Moreover, in the presence of a certain amount of acid, chitosan can be dissolved in some water-based mixtures such as water/methanol and water/acetone.

#### *Chemical Properties*

Similar to the most of biopolymers, chitosan has an amphiphilic character, which could influence its physical properties in solutions and solid state alike. This is attributed to the presence of the hydrophilic amino groups together with the hydrophobic acetyl groups in its molecular structure. The presence of large number of amino groups also confers chitosan a strong positive charge unlike most of polysaccharides.

Chitosan has a cationic nature due to the presence of amino and hydroxyl groups, which render it modifiable by various chemical and physical means including complexation, grafting, crosslinking and blending [81]. Chitosan is a rigid polymer due to the presence of hydrogen bonding in its molecular structure. Consequently, it can be easily transformed into films with a high mechanical strength when casted from solutions. Chitosan is also a weak polyelectrolyte that may be regarded as a very poor anion-exchanger. Therefore, it is likely to form films on negatively charged surfaces in addition to the ability to chemically bind negatively charged fats, cholesterol, proteins and macromolecules [57, 82].

#### *Biological Properties*

Chitosan is a non-toxic natural product [83, 84]. Therefore, it can be applied in the food industry for birds and fur-bearing animals. Moreover, chitosan is metabolised by certain human enzymes, especially lysozyme, and is considered as biodegradable [85, 86]. Chitosan is also biocompatible and, therefore, it can play a role in various medical applications such as topical ocular application [87], implantation [88] or injection [89]. Chitosan also has antibacterial, [90] wound-healing effects in humans [91] and animals [92–95] together with hemostatic activities [96]. It also has bioadhesive ability due to its positive charges at physiological pH [97]. A summary of the physical, chemical and biological properties of chitosan are listed in Table 1 [73, 98].

Table-1: Physical, chemical and biological properties of chitosan.

Physical properties	Chemical properties	Biological properties
White yellow in colour	Degree of acetylation range 70–95%	Biocompatibility
Flakes, bead or powder	Cationic polyamine	Natural polymer
High molecular weight ( $1.2 \times 10^5 \text{ g mol}^{-1}$ )	High charge density at pHs < 6.5	Safe and non-toxic
Viscosity, high to low	Forms gels with polyanions	Haemostatic
Intermolecular hydrogen bonding	Linear weak polyelectrolyte	Biodegradable to normal body constituents
Amorphous solid	Adheres to negatively charged surfaces	Bacteriostatic / Fungistatic
Density range 0.18 to $0.33 \text{ g cm}^{-3}$	Chelates certain transitional metals	Spermicidal
Soluble in diluted aqueous acid solution e.g., acetic acid	Amiable to chemical modification	Anticancerogen
Insoluble in water, alkali and organic solvents	Reactive amino/hydroxyl groups	Anticholestermic

### Applications of Chitosan

In the medical and pharmaceutical fields, chitosan can be used for promoting weight loss [99]. This is due to its capability of binding a high amount of fats (about 4 to 5 times its weight) compared to other fibres. In addition, chitosan has no caloric value as it is not digestible, which is a significant property for any weight-loss product [100]. Therefore, it is used as a cholesterol-reducing agent [101]. Chitosan is also used as a wound-healing agent [102, 103, 94] in the form of a bandage [104], burns dresser [105], drug carriers [106–108], drug-delivery system [109–111], preventing heart disease, controlling high blood pressure, preventing constipation, reducing blood levels of uric acid and producing artificial kidneys [112] due to the high mechanical strength of its membrane. In the eye-wear industry, chitosan has been used in producing contact lenses [113–115] as it is more biocompatible than those made of synthetic polymers [105]. In cosmetics and personal care [116], chitosan is used in making face, hand and body creams. In addition, it can be applied for bath lotion and hair treatment due to its cationic charge, which allows it interact easily with negatively, charged tissues like skin and hair [117].

In the chemical industry, chitosan is also used in the paper manufacturing as a thickener for printing and in coating paper because it is capable of interacting with fibers to form some bonds such as ionic, covalent and Van der Waals forces bonds which enhance paper stability and its resistance to outer influences [71]. In addition, owing to the smoother surface and resistance to moisture of the paper produced with chitosan, chitosan is used in the

production of toilet paper, wrapping paper and cardboard. In the photography field, chitosan is used for the rapid development of pictures.

In agriculture, chitosan is safely used for controlled agrochemical release, seed coating [118] and making fertilizer due to its biodegradability and natural origin. Recently, there has been some concern over its use in tissue engineering [57, 35, 119].

In environmental applications, chitosan plays an important role in wastewater treatment and industrial toxic pollution management [71, 120] as it has the ability to adsorb dyes, pesticides, and toxic metals from water and wastewater. In addition, fibers of chitosan containing some enzymes are used in making filters for gas masks as they detoxify harmful gases [121]. A summary of some applications of chitosan is shown in Table 2. More details on the various applications of chitosan can be found in recently published reviews [108, 122, 123].

### Chitosan Blends

Polymer blending is a simple method for obtaining desirable polymeric materials with combined properties originated from components for particular applications [30]. Recently, blends of natural polymers have been becoming considerably important due to their strong potential in replacing synthetic polymers in many applications [124] in addition of being renewable resources, nontoxic, inexpensive and leave biodegradable waste [125]. Among natural polymers, chitosan and its blends have received special interest due to its versatility and suitability for a large number of applications as discussed earlier. Chitosan properties are enhanced by blending with synthetic and naturally occurring macromolecules and therefore, this area has attracted much attention in recent years in various occasions [126–130].

Generally, there are two main methods that are commonly used in the blending of chitosan: 1) dissolving in a solvent followed by evaporation (solution blending) [131, 132] and 2) mixing under fusion conditions (melt blending) [133]. However, according to the literature, solution blending is the most applied method for preparing chitosan blends. This is due to its simplicity and suitability for producing various forms of chitosan blends (beads, microspheres, films and fibers).

Table-2: Some applications of chitosan.

Application	Examples	Reference	
Water treatment	Filtration	[57]	
	Removal of metal iron	[57]	
	Bandages, Sponges	[104]	
	Cholesterol reducing agent	[101]	
	Tumor inhibition	[57]	
	Membranes	[57]	
	Dental plaque inhibition	[57]	
	Skin burns/Artificial skin, Contact lens	[57]	
	Medical	Controlled release of drugs	[113–115]
		Bone disease treatment	[57]
Wound healing agent		[57]	
Drug carriers		[102,103,94]	
Dressing burns		[106–108]	
Drug delivery system		[105]	
Producing artificial kidneys		[109–111]	
Make-up powder		[112]	
Nail polish		[57]	
Moisturizer		[57]	
Cosmetics	Bath lotion and hair treatment	[117]	
	Face, hand and body creams	[116]	
	Toothpaste	[57]	
	Surface treatment	[57]	
Paper industry	Photographic paper	[57]	
	Carbonless copy paper	[57]	
Biotechnology	Enzyme immobilization	[57]	
	Protein separation	[57]	
	Glucose electrode	[57]	
	Chromatography	[57]	
Agriculture	Seed coating	[118]	
	Hydrophobic/Fertilizer	[57]	
Food	Removal of dyes, solids, acids	[57]	
	Animal feed additives	[57]	
	Color stabilization	[57]	
Chemical industry	Solvent separation	[57]	
	Permeability control	[57]	

In solution blending, chitosan is dissolved in an appropriate solvent (usually diluted acetic acid) with continuous stirring at room temperature. This is followed by mixing a desired amount of another polymer after being dissolved in a solvent under continuous stirring conditions. The blend solution of chitosan is often crosslinked by addition of a crosslinking agent to improve mechanical properties. Subsequently, the blend solution is filtered and then cast on a glass plate or a petri dish and left to dry under room or oven temperature [134,135]. Eventually, the blend is washed with NaOH solution to remove the excess acetic acid. Table 2 presents a summary of the preparation of some chitosan blends using the casting method.

Like other polymer blends, the properties of chitosan blends depends upon the miscibility of its components at the molecular scale, which takes place as a result of specific interactions between the chains of polymeric components. The most common interactions in the chitosan blends are: hydrogen bonding, ionic and dipole bonds,  $\pi$ -electrons and charge-transfer complexes. Various techniques such

as thermal analysis [136], electron microscopy [137], viscometric measurements [138] and dynamic mechanical studies [139], have been used to investigate the polymer–polymer miscibility in solutions or in solid state.

The purposes of chitosan blending vary depending upon the application demands. This includes the following: 1) to enhance hydrophilicity [140, 141], 2) to enhance mechanical properties [142–146], 3) to improve blood compatibility [147–149] and 4) to enhance antibacterial properties [150]. In blood contact applications, chitosan promotes surface-induced thrombosis and embolization [147–149].

The selection of the polymers to be blended with the chitosan depends on the property to be conferred or boosted. For example, the hydrophilic property of chitosan is modified by blending with polymers such as PEG and PVA [140, 141]. Chitosan was also blended with several polymers such as polyamides, poly (acrylic acid), gelatin, silk fibroin and cellulose to enhance mechanical properties [142–

146]. To enhance antibacterial properties, chitosan is blended with cellulose<sup>150</sup>.

#### *Blends of chitosan with synthetic polymers*

Blending of chitosan with synthetic polymers is an attractive method for preparation of synthetic biodegradable polymers with enhanced properties, such as good water retention and enhanced mechanical properties (e.g., synthetic biodegradable polymers used as biomaterials range in tensile strength from 16 to 50 MPa and modulus from 400 to 3,000 MPa) while maintaining biodegradability [151]. Because of the large applications of chitosan in various fields, blends with synthetic polymers having wide range of physicochemical properties have been prepared in various occasions with solution blending investigated by many workers.

PVA and polyethylene are among the synthetic polymers that have been frequently blended with chitosan [126, 127, 152, 153]. The obtained blends represent new materials with better hydrophilicity, mechanical properties and biocompatibility than the characteristics of single components [154, 155]. The physico-chemical properties of chitosan/PVA blends using sorbitol and sucrose as plasticizers were investigated by Arvanitoyannis *et al.* [156]. Melting point and heat of fusion showed a decreasing trend with increasing the plasticizer content. However, the elongation% and CO<sub>2</sub> as well as water vapor permeability of the blends showed an increase with increasing the plasticizer content coupled with a proportional decrease in tensile strength and modulus.

Graft copolymerization of chitosan with methylmethacrylate (MMA), methacrylic acid, 2-hydroxyethylmethacrylate (HEMA), acrylonitrile and acrylamide has been reported in the literature. Similarly, styrene and vinyl acetate have also been grafted on chitosan. Grafting of chitosan with *N,N'*-dimethylaminoethylmethacrylate (DMAEMA) has also been reported [131, 152, 157–159]. Blends of chitosan with polyurethane were prepared using a solution casting method and their mechanical properties were evaluated [160]. The blends showed poor phase properties were reported.

Hybrid materials of chitosan with polyinosic (viscose rayon) were generated by a mechanical blending method. Chitin and chitosan were reacted with 1,6-diisocyanatohexane [poly-urea (urethanes)] in DMA-LiCl solutions and the blends properties were evaluated [161].

Biodegradable films of chitosan blends containing polyethylene glycol (PEG) or polyvinyl alcohol (PVA) were prepared by mixing PEG or PVA solution with chitosan acetate solution, and films were prepared by the solution casting method [151, 148]. Homogenous films with higher initial temperature of thermal degradation were produced.

Chitosan-blended films containing glycerol (0.25% and 0.5%) were prepared by Butler *et al.* [162]. Oxygen and ethylene permeability of obtained films were found to remain constant during the storage period, but percent elongation decreased.

Shieh and Huang [163] have reported the preparation and characterization of chitosan/*N*-methylol nylon 6 blends in the form of membranes for the separation of ethanol-water mixtures by pervaporation. The obtained blend membranes were treated with H<sub>2</sub>SO<sub>4</sub> to enhance their separation performance. The blend composition was found to play a significant role in affecting the performance of the membranes.

Wiles *et al.* [164] investigated the mechanical properties of chitosan and PEG films. It was revealed that the obtained blend films containing PEG of 0.25% and 0.5% resulted in an increased elongation%, but tensile strength (TS) and water vapor transmission rate (WVTR) were decreased.

The mechanical properties of chitosan films prepared by blending with polyols (glycerol, sorbitol and PEG) and fatty, stearic and palmitic acids were studied by Srinivasa *et al.* [127]. Investigations of the mechanical properties showed a decrease in the tensile strength with the addition of polyols and fatty acids, while the elongation% was increased in polyol-blend films. However, fatty acid-blended films did not show any significant difference.

Attempts to prepare film blends of chitosan with poly (lactic acid) (PLA) were reported by Nugraha *et al.* [165]. The thermal and mechanical properties of the obtained films revealed that chitosan/PLA blends are incompatible, i.e., there was no interaction between the two polymers.

Chitosan blends with polyvinyl pyrrolidone (PVP) and PEG were reported by Zeng *et al.* [166]. The compatibility of the blends was proved by FTIR, wide angle x-ray diffraction (WAXD) and differential scanning calorimetry (DSC). The chitosan/PVP blend showed no porosity unlike the chitosan/PEG blend, which showed high porosity.

The former and latter are attributed to the strong and weak interactions in the blends, respectively.

Sandoval *et al.* [167] studied the compatibility of two chitosan blends with (vinyl alcohol) (PVA) and poly(2-hydroxyethyl methacrylate) (P2HEM) through molecular dynamic simulations. The aim of this study was to find out which of the two functional groups ( $-\text{CH}_2\text{OH}$ ) and ( $-\text{CH}_2\text{OH}$ ), of chitosan is responsible for the interaction. It was concluded that the interaction occurs predominantly with the hydroxymethyl groups of chitosan at low composition of P2HEM and PVA, while the interaction with the amine groups increases with the increase in the composition of the two polymers.

Sarasam and Madihally [168] have reported the preparation and characterization of chitosan/polycaprolactone (PCL) blends at different ratios, temperatures, and humidities, for tissue engineering applications. According to the thermograms (using the Flory–Huggins theory), the two polymers were successfully blended. Measurements of differential scanning calorimetry (DSC) also indicated that there is an interaction between the two components when the results were analyzed using the Nishi–Wang equation. However, no remarkable alterations relative to chitosan were observed during tensile properties measurements, whereas significant improvements were observed after solvent annealing. In addition, a significant improvement in mechanical properties was achieved when a 50:50 ratio blend dried at 55°C was used. It was concluded that such a blend has a potential for various applications in tissue engineering.

Blends of chitosan with poly- $\epsilon$ -caprolactone (PCL), poly (butylene succinate) (PBS), poly (lactic acid) (PLA), poly (butylene terephthalate adipate) (PBTA), and poly (butylene succinate adipate) (PBSA) were prepared by melt processing [133]. For the chitosan/PBS blend, the amount of chitosan varied from 25wt% to 70wt%. The addition of chitosan to PBS or PBSA tends to depress the melting temperature of the polyester. The crystallinity of the polyesters (PCL, PBS and PBSA) containing 50% chitosan decreased. The addition of chitosan to the blends was also found to decrease the tensile strength while increasing the tensile modulus. Chitosan displayed intermediate adhesion to the polyester matrix. Microscopic results indicated that the skin layer is polyester rich, while the core is a blend of chitosan and polyester. Fractured surface of blended chitosan with a high  $T_g$  polymer, such as PLA, displayed a brittle fracture. Blends of chitosan

with PCL, PBTA, or PBSA display fibrous appearances at the fractured surface due to the stretching of the polymer threads. Increasing the amount of chitosan in the blends also reduced the ductility of the fractured surface. The chitosan phase was found to agglomerate into spherical domains and cluster into sheaths. The pull-out of chitosan particles was found to be evident in tensile-fractured surfaces for blends of chitosan with ductile polymers while it was absent in the blends with PLA. PBS displays a less lamellar orientation when compared to PCL or PBSA. The orientation of the polyesters (PCL and PBSA) does not seem to be affected by the addition of chitosan.

Chitosan/nylon 11 blends at different ratios were prepared and characterized by FTIR, scanning electron microscopy (SEM) and x-ray [169]. Biodegradability was also investigated. Results revealed that the physical properties of nylon 11 were greatly affected by the addition of chitosan in the blended films and that good biodegradability of the resulting blends was observed.

Smitha *et al.* [32] have reported the preparation and characterization of the crosslinked blends of chitosan/nylon 66 at different weight compositions. The crosslinking and thermal stability of the blends were confirmed by FTIR and TGA, respectively. The obtained results showed good indication for dehydration of dioxane and moderate water sorption (50–90%) in the blends with no significant effects on the blend mechanical stability. Increasing the water concentration in the feed improved the membrane swelling and as a result the flux was enhanced at a reduced selectivity. Varying the membrane thickness resulted in a remarkable decrease in the flux with some improvement in selectivity. Higher permeate pressures caused a reduction in both flux and selectivity.

Various proportions of three chitosan portions having different molecular weights were blended with poly (N-vinyl-2-pyrrolidone) (PNVP) [170]. The surface properties of the obtained films were studied by scanning electron microscopy (SEM) and contact-angle measurements. It was revealed that the blend surfaces were enriched with a low surface free energy component, *i.e.*, chitosan.

Other studies on chitosan blends and composites were also reported in the literature. For example, chitosan/PEG [171], chitosan/polyethylene oxide [172], chitosan/PVP [173], chitosan/PVA/gelatin [174] and chitosan/PVA/pectin [175].

*Blends of chitosan with natural polymers*

Blending of chitosan with other biopolymers has been proposed as an interesting method to obtain new biomaterials with enhanced properties to meet the requirements of specific applications. Reports on blending of chitosan with biopolymers have been published in various occasions. For example, blending of chitosan with collagen has been reported in several occasions [128, 129, 176–178]. The effect of chitosan on the properties of collagen has also been investigated [30, 179, 180]. The findings of these studies proved that chitosan can modify the mechanical properties of collagen.

Arvanitoyannis *et al.* [142] used chitosan and gelatin aqueous solutions (pH 4.0) to develop membranes by solution casting at 60°C followed by evaporation at 22 or 60°C (low- and high-temperature methods, respectively). The thermal, mechanical and gas/water permeation properties of the obtained composite membranes, plasticized with water or polyols, were investigated. The increase in the total plasticizer content led to a considerable decrease in elasticity modulus and tensile strength, whereas the elongation % increased. The low-temperature preparation method was found to lead to a higher percentage of renaturation (crystallinity) of gelatin and therefore, a decrease of 1–2 orders of magnitude in the permeability of CO<sub>2</sub> and O<sub>2</sub> in the chitosan/gelatin blend membrane was observed. The increase in the total plasticizer content (water or polyols) in the membranes was found to produce a proportional increase in their gas permeability.

Ikejima *et al.* [26] reported the development biodegradable polyester/polysaccharide blend films made of microbial poly (3-hydroxybutyric acid) (PHB) with chitin and chitosan. The DSC analysis revealed that crystallization of PHB in the blends was suppressed when the content of polysaccharides increased. Similar tendency was proved by variation in band intensity of the carbonyl stretching absorption originated from PHB as shown by FTIR. The suppression of crystallization of PHB is found to be more profound by blending of chitosan than chitin. PHB in the blends was found (by <sup>13</sup>C NMR spectroscopy) to be trapped in the 'glassy' environment of the polysaccharide. The chitosan resonances in the blends were significantly broadened compared to those of chitin. This was attributed to formation of hydrogen bonds between the carbonyl groups of PHB and the amide -NH groups of chitin and chitosan. The crystallization behavior and environmental biodegradability were also investigated for the films made of poly (3-

hydroxybutyric acid) (PHB), a semi-crystalline polymer, blended with chitin and chitosan [27]. The structural analysis of blended films with XRD revealed peaks representing PHB crystalline component. This was attributed to ability of XRD to detect the remaining thickness of the lamella of the PHB crystalline component in the blends. However, such lamellar thickness was too small to show an observable melting endotherm in the DSC thermogram and in a crystalline band absorption in the FTIR spectrum. The dynamic mechanical thermal analysis showed that the thermal transition temperatures of PHB amorphous regions were similar to that of neat PHB for both PHB/chitin and PHB/chitosan blends. It was also finally reported that both PHB/chitin and PHB/chitosan blended films were biodegrade when environmentally tested.

Preparation of chitosan/κ-carrageenan blends in the form of films has been studied. The effect of the type of solvent (acetic, lactic, citric, maltic and ascorbic acids) on the mechanical properties of the obtained films was investigated [181]. Ascorbic acid was found to increase the tensile strength and elongation % of the films compared to other diluting acids. These results suggested that there are interactions among the organic acids and κ-carrageenan and chitosan.

Other types of aqueous blends based on chitosan were also reported. For example, the preparation of aqueous blends of chitosan with protein was reported by Kweon *et al.* [182]. *Antheraea pernyi* silk fibroin (SF)/chitosan-blended films were prepared by mixing an aqueous solution of *A. pernyi* SF and acetic acid of chitosan. The conformation of *A. pernyi* SF in the blended films was suggested to be in a form of β-sheet structure, mainly due to the effect of using acetic acid as a mixing solvent. The thermal decomposition of chitosan was found to be improved by blending with *A. pernyi* SF.

Cheung *et al.* [28] investigated the phase structure of poly (*R*)-(3-hydroxybutyrate) (PHB)/chitosan and poly (*R*)-(3-hydroxybutyrate-co-3-hydroxyvalerate) (P(HB-co-HV))/chitosan blends using <sup>1</sup>H CRAMPS (combined rotation and multiple pulse spectroscopy). A modified BR24 sequence that yielded intensity decay to a zero mode rather than the traditional inversion-recovery mode was used to measure <sup>1</sup>H *T*<sub>1</sub>. It was observed that a single exponential *T*<sub>1</sub> decay for the β-hydrogen of PHB or P (HB-co-HV) exists at 5.4 ppm and for the chitosan at 3.7 ppm. *T*<sub>1</sub> values of the blends are either faster or intermediate to those of the plain polymer



components. The  $T_{1\rho}$  decay of  $\beta$ -hydrogen is bi-exponential. The slow  $T_{1\rho}$  decay component is interpreted in terms of the crystalline phase of PHB or P (HB-co-HV). The degree of crystallinity decreased with the increase in the content of chitosan in the blend. The fast  $T_{1\rho}$  of  $\beta$ -hydrogen and the  $T_{1\rho}$  of chitosan in the blends either follow the same trend as or are faster than the weight-averaged values based on the  $T_{1\rho}$  of the plain polymers. The DSC analysis of the blends revealed a decrease in the melting point in addition to one effective  $T_g$  in the blends. The results suggested that chitosan is miscible with either PHB or P(HB-co-HV) at all compositions.

The thermo-mechanical properties films of chitosan, starch/chitosan and pullulan/chitosan casted from solutions using dynamic mechanical thermal analysis (DMTA) and large deformation tensile testing were investigated by Lazaridou and Biliaderis [183]. Incorporation of sorbitol (10% and 30%) as well as adsorption of moisture by the films resulted in a remarkable reduction in the glass transition ( $T_g$ ) of the polysaccharide matrix due to plasticization. The separate phase transitions of the individual polymeric components and the separate polyol phase in the blended films were not clear. A rather broad but single drop of elastic modulus ( $E'$ ) and a single  $\tan \delta$  peak were observed. Adjusting the films with various levels of moisture/polyol during tensile test led to large drops in Young's modulus and tensile strength ( $\sigma_{max}$ ) with the rise in levels of polyol and moisture. The sensitivity of films to plasticization was in the order of: starch/chitosan > pullulan/chitosan > chitosan.

A series of chitosan/gelatin blend films has been reported in various occasions<sup>184</sup>. Reasonable compatibility and better water retention were observed in chitosan films. The chitosan/gelatin blend showed higher percentage of elongation-at-break together with lower Young's modulus. In addition, the average water contact angles of the obtained films were found to be 60°. The obtained chitosan/gelatin films were tested for oxygen permeability, optical transmittance, water absorptivity and mechanical properties by Yuan and Wei [115]. The authors found an increase in water absorption together with an improvement in permeability of oxygen as well as the solute in chitosan/gelatin films. These films were also found to be more transparent, flexible and biocompatible.

Zhai *et al.* [185] studies the preparation of antibacterial films of blended chitosan/starch by prepared by irradiation of compression-molded, starch-based mixtures in a physical gel state with an electron beam accelerator at room temperature. The

incorporation of 20% chitosan into the starch film led to a significant improvement in the tensile strength and the flexibility of the starch film. In addition, observing the blended starch/chitosan film with XRD and SEM analyses revealed that the presence of an interaction and microphase domain separation between the starch and chitosan molecules. Moreover, the films of blended starch/chitosan were irradiated to suitable dose to produce antibacterial films. The irradiation was found to have no impact on the structure of the blended starch/chitosan films. However, antibacterial activity that was induced in the films having chitosan concentration as low as 5% was accompanied by degradation of the bended chitosan under the influence of irradiation.

Membranes composed of chitosan and cellulose blends dissolved in trifluoroacetic acid were prepared by Wu *et al.* [150]. Investigation with the mechanical and dynamic mechanical thermal analyzers showed that the cellulose/chitosan blends are almost incompatible. In addition, results obtained from water vapor transpiration rate and antibacterial measurements suggested that the membranes of chitosan and cellulose blends have strong potential for wound dressing application mainly due to their antibacterial properties.

Preparation of biodegradable films of chitosan with polylactic acid blends was reported by Suyatma *et al.* [29] using solution mixing and film casting methods. The incorporation of polylactic acid with chitosan in the blends enhanced the water barrier properties while decreasing the sensitivity of the chitosan films towards water. However, the tensile strength and elastic modulus of chitosan were found to decrease with the addition of polylactic acid. The chitosan and polylactic acid blends were found to be incompatible as revealed by measurements of mechanical and thermal properties. This was confirmed from the results of FTIR spectral analysis, which showed the absence of specific interactions between chitosan and polylactic acid.

Mucha and Pawiak [186] reported that films made of chitosan/ hydroxylpropyl cellulose blends showed good miscibility of components with better optical transparency and improved mechanical properties. The phase separation of the components occurred more drastically after water removal due to the active compatibilisation behaviour of the water molecules in this system, which lead to the formation of additional hydrogen bonds.

Chitosan and starch blend films were prepared and characterized by Xu *et al.* [187]. The

obtained films showed a decrease in the water vapor transmission rates together with an increase in the tensile strength and the elongation %-at-break with increasing starch ratio in the blend. FTIR spectroscopy and x-ray diffraction of the blends have suggested the existence of interactions and compatibility of the two film-forming components.

Wittaya-areekul and Prahsarn [188] investigated the possibility of incorporation of corn starch and dextran with chitosan using glutaraldehyde, a crosslinker and used the obtained blends in wound dressing applications. The effect of adding polypropylene glycol (as a plasticizer) on the chitosan blends was also reported. Results showed that corn starch and dextran can be incorporated into chitosan film to improve the physical strength, *i.e.*, vapor penetration, water uptake, and oxygen penetration properties. The addition of propylene glycol was found to improve the film elasticity and all other properties mentioned already with the exception of bio-adhesive properties.

Yin *et al.* [189] examined the miscibility of chitosan blends with two cellulose ethers, *i.e.* hydroxypropylmethylcellulose and methylcellulose by infrared spectroscopy, thermal gravimetric analysis, wide-angle X-ray diffraction and scanning electron microscopy. It was concluded that full miscibility cannot be achieved if the hydrogen bonding between the polymers is weak.

The miscibility of chitosan/gelatin blends in a buffer solution (0.2 M sodium acetate and 0.1 N acetic acid) has been assessed by means of viscosity, ultrasonic and refractive index methods at 30 and 50°C [190]. The obtained data indicated that the blend is immiscible in all compositions, and the variation of medium temperature has no influence on miscibility of the blend.

The compatibility of chitosan/collagen blends was evaluated by dilute solution viscometry [191]. The obtained data showed that collagen/chitosan blends are miscible at any ratio in acetic acid solutions at 25°C. As far as the “memory effect” is concerned, the blends are also miscible in the solid state.

Elhefian *et al.* [192] reported the preparation and characterization of chitosan/agar-blended films. The FTIR results and thermal analysis showed that

the interactions (intermolecular hydrogen bonding) among the functional groups of the blend components can occur.

A summary of some chitosan blends with synthetic and natural polymers including their preparation by the casting techniques suggested by some authors is presented in Table 3.

#### *Some Applications of Chitosan Blends*

According to the literature, most of the applications of chitosan blends are in the pharmaceutical and biomedical fields. For example, chitosan has been receiving increasing interest in drug delivery applications due to its capacity in enhancing the transport of hydrophilic drugs. Chitosan has been also reported to be useful in colon- or nasal delivery and as a carrier in gene delivery. Several chitosan nanocomposites were evaluated based on the ionotropic gelation. Numerous chitosan/DNA nanoparticles were framed from the complexation of the cationic polymer with DNA plasmids. Such particles is formed by ionic interaction chitosan as a cationic polymer and DNA anions.

In the area of drug delivery systems, chitosan blends have been widely used for drugs control release because of their advantageous properties, such as non-toxicity, biocompatibility, biodegradability and availability of terminal functional groups [197]. Various physical forms of chitosan blends, such as microparticles [198], tablets [199], films [200], beads [201], gels [202] were proposed for various drug release applications and as an absorption enhancer for nasal and oral drug delivery [203]. For example, various blends of collagen and chitosan were used for the architecture of membranes for controlled release [176, 177, 204]. This also included proposing chitosan as a useful excipient for obtaining sustained release of water-soluble drugs and for enhancing the bioavailability of poorly water-soluble compounds. Moreover, chitosan has also been presented as a useful polymer for colon-specific and oral administered drug delivery [205]. This has derived huge research efforts that led to the publication of an immense number of studies for a wide variety of applications in the field of controlled release (over 2,000 papers in the last 15 years), which makes it impossible to be reviewed here.

Table-3: A summary of some chitosan blends with synthetic and natural polymers including their preparation by the casting technique suggested by some authors.

Chitosan source (DD)	Solvent used	Blend	Crosslinker	Plasticizer	Film thickness	Ref.
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Shrimp/85%	1%(v/v) acetic acid	CS/glycerol CS/sorbitol CS/PEG CS/tween60 CS/tween 80	-	-	2.82– 3.95 × 10 <sup>-2</sup>	[193]
91%	1%(w/v) acetic acid	CS/gelatin	-	-	-	[115]
Crab/80-85%	2.0 wt% acetic acid	CS/cellulose	-	-	-	[150]
	1% acetic acid	CS/PLA	-	-	-	[29]
Shrimp/80%	2% acetic acid	PA/CS	Glutaraldehyde	-	-	[194]
Crab/> 85%	1% acetic acid	CS/gelatin	-	-	-	[184]
56%	5% acetic acid+1% HCl (catalyzer)	HPC/CS	Glyoxal and glutaraldehyde	-	20-30µm	[153]
96% Lactic acid CS/cornstarch Glutaraldehyde Propylene (8)	Lactic acid	CS/cornstarch CS/dextran	glutaraldehyde	Propylene glycol (PG)	-	[188]
60%	(0.2 M sodium CS/gelatin (9) acetate + 0.1 N acetic acid)	CS/gelatin	-	-	-	[190]
95.7%	1% acetic acid	CS/CE	-	-	-	[189]
90%	1% (v/v) lactic acid	CS/starch	-	Glycerin	~ 2.54 µm	[187]
-	2% acetic acid	CS/PVA	-	Sorbitol and sucrose	-	[156]
91%	2% acetic acid	CS/PVP CS/PEG	-	-	40–60 µm	[166]
85%	0.5M acetic acid	CS/ collagen	-	-	-	[191]
~ 84%	trifluoroacetic acid (TFA)	CS/nylon 11	-	-	-	[169]
85, 87 and 93%	4 wt% acetic acid	(PNV2P)/CS	-	-	40–50 µm	[170]
84%	Formic acid	CS/ nylon 66	sulfuric acid	-	-	[32]
~ 85%	0.5M acetic acid	CS/ PCA	-	-	50–60 µm (dry) and 90–120 µm (wet)	[168]
-	88 wt% formic acid	CS/ NMN6	1M H <sub>2</sub> SO <sub>4</sub>	-	20–40 µm	[163]
80%	0.5% (v/v) acetic acid	CS and poly (sodium-4-styrene sulphonate)	-	-	-	[195]
75–85%	2% acetic acid	CS/PVA	-	-	-	[196]

The tissue engineering field is another biomedical field where chitosan and its blends are receiving growing interest. Chitosan-based materials that have been proposed for tissue engineering are present in different physical forms, including porous scaffolds and gels [35, 206–208]. For example, blends of collagen and chitosan have been used for the design of polymeric various scaffolds for the *in vitro* culture of human cells and skin as well as implant fibers [128, 209].

As an anti-microbial agent, chitosan is a biopolymer that has been well known for its ability to accelerate the healing of wounds in humans [210]. Chitosan was reported to stimulate the migration of polymorphonuclear (PMN) and mononuclear cells. It also accelerates the re-epithelialization and normal skin regeneration [211]. The presence of polycationic

nature in chitosan conferred it an antimicrobial activity against a variety of bacteria and fungi [212]. In particular, the interaction between negatively charged microbial cell walls and positively charged chitosan leads to the leakage of intracellular constituents. Moreover, the binding of chitosan with DNA and inhibition of mRNA synthesis occur through chitosan penetration into the nuclei of the microorganisms and its interfering with the synthesis of mRNA and proteins. Furthermore, chitosan is a biomaterial that is widely used for effective delivery of many pharmaceuticals [213]. Hence, it has a strong potential for incorporating other antipyrotics for the preparation of long-acting antibacterial wound dressings.

In environmental applications, due to its powerful chelating ability, chitosan was found to be

among the most powerful heavy metal ion binders [214]. This is performed mainly with the use of chitosan-based powders, flakes, gel beads, composite membranes or others [215–217]. In general, the affinity of chitosan to heavy metal ions is as follows: Pd>Au>Hg>Pt>Cu>Ni>Zn>Mn>Pb>Co>Cr>Cd>Ag [75, 218, 219]. Chitosan blends can be also applied for the dehydration of some solvents. For example, it has been reported that chitosan/N-methylol nylon 6 blend membranes can be used for the separation of ethanol-water mixtures under various parameters including acid (H<sub>2</sub>SO<sub>4</sub>) post-treatment, feed concentration, blend's ratio and temperature [163]. Recently, some chitosan-blended films have been developed for food packaging applications [220–222]. This is mainly due to their antimicrobial activity, good water resistance, biodegradability, good thermal properties, biocompatibility and non-toxicity.

### Conclusion

Chitosan is a natural polymer that has proposed for a wide variety of applications ranging from food packaging to a drug carrier. In this review, an attempt has been made for better understanding of chitosan and its blends in various aspects. This includes its physical, chemical and biological properties as well as the preparation and characterization of its blends with other materials and their applications.

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### LIST OF ABBREVIATIONS

The following abbreviations have been used in the text:

CS	Chitosan
DD	Degree of deacetylation
PA	Polyaniline
PVA	Poly vinyl alcohol
PEG	Polyethylene glycol
PLA	Poly lactic acid
PVP	Polyvinyl pyrrolidone
HPC	Hydroxyl propyl cellulose
P2HEM	Poly (2-hydroxyethyl methacrylate)
PNV2P	Poly (N-vinyl-2- pyrrolidone)
MMN6	N-methylol nylon 6
PCA	Poly caprolactone
PG	Propylene glycol
CE	Cellulose ethers

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