TURUN YLIOPISTO

Natural organic polymers in sustainable health technologies

Master of Science in Technology
Health Technology Materials
Materials Engineering
Department of Mechanical and Materials Engineering

Author:
Jasmine Serén

Supervisor:
Professor Emilia Peltola

28.05.2025
Turku

The originality of this thesis has been checked in accordance with the University of Turku quality assurance system using the Turnitin Originality Check service.

Master of Science in Technology Thesis

Subject: Materials Engineering
Author: Jasmine Serén
Title: Natural organic polymers in sustainable health technologies
Supervisor(s): Professor Emilia Peltola
Number of pages: 56 pages
Date: 28.05.2025

Sustainability concerns within health technology and healthcare sector have increased in the past few years as climate change and environmental degradation have continued to occur at an expedited speed. Healthcare services on their own account for 4.4% of the global net greenhouse gas (GHG) emissions which makes them a prominent category within global GHG emissions assessments reports. One of the key ways to influence the GHG emissions of health technologies utilized in healthcare services, is to make adjustments in what materials are preferred for the manufacturing of health technology products, such as health monitoring devices. Collagen, chitosan and alginate offer a variety of options for material sourcing from currently existing industries such as fishing, meat or leather. The previously mentioned industries often discard processing waste and by-products such as bones, shells, skin and guts which could be utilized to produce high-value biomass for health monitoring application purposes.

It's important to examine sustainable material sourcing from the perspective of material safety, availability as well as environmental and social impact. Among the three chosen materials for this thesis, bovine-derived collagen is the most commonly utilized material due to its long research history, abundance of raw materials as well as favorable properties including biocompatibility and low immunogenicity. Few of the key hinderances for bovine-derived collagen are the risks for zoonosis diseases, population intolerances, and dependency on cattle for raw materials as well as religious concerns. Marine-derived collagen represents a promising alternative to bovine-derived collagen as it is considered to be safer due to lowered risks of transmissible diseases, and it offers an opportunity to valorize previously underutilized fish waste.

When considering marine-derived collagen and crustacean-derived chitosan, it’s important to note that overfishing is one of the main material concerns. Insect and fungi derived chitosan offer fast material renewability and superior material properties such as antimicrobial activity and lowered risks of allergic reactions when compared to traditional crustacean-derived chitosan. While collagen and chitosan are most often derived from animal sources, alginate is mainly acquired from brown algae. Alginate sourced from brown algae exhibits good non-immunogenicity, non-toxicity and biocompatibility properties and presents a beneficial way to decrease pressure on land resources as well as to applying traditional cultural knowledge from coastal areas.

Keywords: organic polymers, sustainability, health monitoring, collagen, chitosan, alginate, material sourcing

Diplomityö, materiaalitekniikka

Tutkinto-ohjelma, oppiaine: Materiaalitekniikan tutkinto-ohjelma (DI), Terveysteknologian materiaalien linja
Tekijä(t): Jasmine Serén
Otsikko: ”Luonnolliset orgaaniset polymeerit kestävissä terveysteknologioissa”
Ohjaaja(t): Apulaisprofessori Emilia Peltola
Sivumäärä: 56 sivua
Päivämäärä: 28.05.2025

Kestävyys kysymykset terveysteknologian ja terveydenhuollon sektorilla ovat lisääntyneet viime vuosien aikana, sillä ilmaston muutos sekä luonnon heikkeneminen tapahtuu kiihtyvässä vauhdissa. Terveydenhuollon palvelut itsessään tuottavat 4,4 % maailman netto kasvihuonekaasupäästöistä, minkä takia sektori on erottuva kategoria maailmanlaajuisissa kasvihuonepäästöjen arviointiraporteissa. Yksi keskeisistä tavoista vaikuttaa terveysteknologiasta aiheutuviin päästöihin terveydenhuollossa, on tekemällä muutoksia siihen mitä materiaaleja suositaan terveysteknologian tuotteiden, kuten monitorointilaitteiden, tuotannossa. Kollageeni, kitosaani ja alginaatti tarjoavat laajat mahdollisuudet materiaalien hankintaan olemassa olevista teollisuuden aloista, kuten kalastuksesta, lihatuotannosta sekä nahkateollisuudesta. Edellä mainitut teollisuuden alat tuottavat nykyiseltään sellaista jätettä ja sivutuotteita, kuten luut, äyriäisten kuoret, nahka ja sisäelämiä, joita voitaisiin hyödyntää korkealaatuisen biomassan tuottamiseen terveysteknologian tarpeisiin.

On tärkeää tarkastella kestävää materiaalihankintaa materiaaliturvallisuuden, saatavuuden sekä ympäristö- ja sosiaalisten vaikutusten kannalta. Diplomityössä käsitellyistä materiaaleista, nautaperäinen kollageeni on yleisimmän käytetty materiaali sen pitkän tutkimushistorian, raaka-aineiden runsauden sekä suotuisten ominaisuuksien kuten bioyhteensopivuuden sekä immunogeenisyyden vuoksi. Keskeisimpiä ongelmia nautaperäisessä kollageenissa ovat riski zoonoosi tautien leviämisestä, väestön intoleranssit, raaka-aine riippuvuus lihatuotannosta sekä uskonnolliset syyt. Meriperäinen kollageeni tarjoaa lupaavan vaihtoehdon perinteiselle nautaperäiselle kollageenille, sillä sitä luonnehditaan turvallisemmaksi materiaaliksi alhaisemman zoonoosi tauti riskien vuoksi ja meriperäinen kollageeni tarjoaa mahdollisuuden hyödyntää aiemmin alihyödynnettyä kalajätettä.

Tarkasteltaessa meriperäisen kollageenin sekä äyriäisistä saatavan kitosaanin materiaalihankintaa, on tärkeää huomioida, että yksi keskeisimmistä ongelmista on riski ylikalastuksesta. Hyönteisistä ja sienistä saatava kitosaani on nopeasti uusiutuva materiaali ja myös materiaalin omaisuudet kuten antimikrobinen toiminta sekä alentunut allergeenisen reaktion riski, ovat paremmat kuin perinteisellä äyriäisistä saatavalla kitosaanilla. Kollageeni ja kitosaani ovat yleensä eläinperäisiä, kun taas alginaatti hankitaan pääsääntöisesti ruskeista levistä. Ruskeista levistä peräisin oleva alginaatti on ei-immunogeeninen, myrkytön ja bioyhteensopiva sekä helpottaa maaresurssien käyttöpainetta ja mahdollistaa rannikkoalueiden perinteisen kulttuuritiedon hyödyntämisen materiaalin valmistukseen.

Avainsanat: Orgaaniset polymeerit, kestävyys, terveysmonitorointi, kollageeni, kitosaani, alginaatti, materiaalin hankinta

Table of contents

1 Introduction

Sustainability has been and continues to be a central topic of discussion within society and science due to climate change and environmental degradation occurring at an expedited speed due to human activities such as heat production, transportation, healthcare services and manufacturing [1]. Many of the currently existing industries such as meat, leather and fishing generate by-products and waste which can be utilized in health technology for novel material manufacturing. By utilizing these otherwise discarded by-products in health technology, new high-value biomass is produced, and already existing materials are put to use (close-loop system) instead of acquiring new materials. With the arrival of artificial intelligence, and the desire for non-invasive as well as sustainable healthcare options, biodegradable and non-invasive health monitoring sensors and electronic devices have emerged.

The aim of this thesis is to take a closer inspection on what are the common agreed definitions for sustainability from the perspective of the United Nations and the European Union as well as to discuss the current protocols, standards and regulation for greenhouse gases, health technology assessment and sustainability overall. The natural organic polymers reviewed in this thesis are collagen, chitosan and alginate as these materials can be derived from a wide range of natural resources and there has been considerable research done on them over the years to prove their compatibility in biomedical applications. As sustainable material is not only defined by it being organic, the later chapters of this thesis also examine the sources from which collagen, chitosan and alginate can be derived from as well as research into the environmental and ethical impacts of the material sources. Since these materials are inspected for the purpose of being utilized in health technology applications, material safety is also explored.

2 Sustainability

The one of the most prevalent definitions for sustainability can be traced to the United Nations Brundtland Commission report of 1987 (“Our Common Future) in which sustainability was defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” [2].

Sustainability is a multifaceted topic which should be approached from an economic, sociocultural and environmental point of view to assess the full range of consequences on the global scale. These approaches or pillars oftentimes go by the abbreviation ESG which stands for Environmental, Social and Governance. Each of the sustainability approaches trickle down to one another and as such by modifying one aspect, the whole equation is affected. Environmental sustainability includes but is not limited to issues concerning reducing waste and emissions (such as carbon and greenhouse gas), preserving biodiversity and conserving natural resources which comprise of water, air, plants, animals and minerals.

2.1 Greenhouse gases and carbon footprint

Greenhouse gases, also known as GHGs, are defined as gases which confine heat in the atmosphere and thus enable life on earth by maintaining the global surface temperature at 14 — 15˚C [3]. GHGs are necessary in moderation to sustain life, however the generous accumulation of GHGs in the atmosphere due to human activities leads to climate change at an expedited speed. One of the most prevalent effects of climate change is the extreme weather conditions such as heat waves and droughts [4]. Human activities, such as electricity and heat production (31%), agriculture (11%), transportation (15%), forestry (6%) and manufacturing (12%) are the most significant GHG sources. [1] In addition to previously mentioned GHG sources, healthcare services are also a significant source of GHGs as they contribute 4.4% of net GHG emissions globally and in industrialized nations the percentage is approximately 10% [4, 5].

In the United Nations Framework convention on climate change (Paris Agreement 2015), it was established that there are 7 GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) [6]. According to the Emissions Database for Global Atmospheric

Research (EDGAR), fossil carbon dioxide emissions contribute for 73.7% of total global emissions while methane accounts for 18.9% of global emissions [6]. Respectively nitrous oxide and fluorinated gases (F-gases) account for 4.7% and 2.7% [6]. From 1990 to 2023, the global carbon dioxide emissions increased by 72.1% while methane increased by 28.2% and nitrous oxide emissions by 32.4% [6]. The biggest growth in GHG emissions between 1990 and 2023 has happened with F-gas emissions, as their consumption has increased by 294% [6].

Fluorinated gases (F-gases), such as HFCs, PFCs, SF_6 and NF_3, are synthetically manufactured gases which are commonly utilized in aerosol sprays, industrial manufacturing processes, refrigeration, electric power transmission and electronics [7]. F-gases were originally created as an alternative for ozone-depleting substances (ODS) however, it was later discovered that F-gases in actuality trap heat from the sun quite efficiently and accelerate global warming [7]. F-gases only make 2.7% of all global GHG emissions but their impact on global warming is oftentimes thousands-fold greater than that of carbon dioxide [7].

2.2 Carbon Emission

Carbon dioxide (CO_2) is a naturally occurring compound which is generated by animals during external respiration and through decomposing of biomass but most of the carbon dioxide emitted into the atmosphere is through human activities [3]. CO_2 is the primary greenhouse gas that is released into the atmosphere mainly through combustion of fossil fuels used in transportation vehicles and to generate electricity [3]. In several industrial processes CO_2 is emitted through fossil fuel consumption during the chemical reactions instead of combustion [3]. Numerous industrial processes utilize electricity in addition to fossil fuels and as such indirectly produce CO_2 from electricity generation [3]. To understand the full carbon emission impact of a product or a process, both direct and indirect emission sources in the value chain need to be outlined.

2.3 Greenhouse Gas Protocol and Scopes

The Greenhouse Gas Protocol (2022) has created an extensive global standardized framework to quantify and manage GHG emissions in public and private sector activities. One of the

ways GHG emissions can be quantified through are scopes and currently there are 3 distinct scopes that can be utilized to obtain the total emissions of a value chain.

Scope 1 emissions are categorized as direct GHG emissions secondary to energy use that are generated from sources which are owned by an organization or are under the jurisdiction of an organization (e.g., company facilities and company vehicles) [8]. Scope 1 quantifies the emissions that an organization can directly influence through their internal policies [8]. Within scope 1, the direct emissions produced through the combustion of fossil fuel can be categorized into 4 groups: stationary combustion, mobile combustion, fugitive emissions and process emissions [8].

Stationary combustion covers carbon dioxide, methane and nitrous oxide emission sources originating from the combustion of fuels, most often they are sources correlated with heating buildings or chemical and physical industrial applications, for instance gas-fired combined heat and power plants [8]. Oftentimes the source for stationary combustion is fossil fuels, however non-fossil biomass (e.g., biomass-derived gases or waste from agricultural sources) may be utilized for combustion in stationary combustion sources. Non-fossil biomass can be fired either independently or simultaneously with fossil fuels [9]. The Greenhouse Gas Protocol states that carbon dioxide emission released through biomass combustion at stationary sources are reported and tracked separately from fossil fuel combustion as biomass CO_2 emissions [9]. Biomass CO_2 emissions indicate the total amount of biogenic carbon dioxide released and they are not included in the overall carbon dioxide equivalent emissions inventory [9]. Greenhouse gases methane (CH_4) and nitrous oxide (N_2O) originating from biomass are reported in the overall carbon dioxide equivalent emissions inventory [9].

Mobile combustion covers the GHG emissions released through combustion of fuel of vehicles leased or owned by an organization [8, 9]. Scope 1 also includes fugitive emissions originating from refrigeration and air conditioning systems as well as other gases from fire suppression systems and release of industrial gases that inadvertently may have leaked or there is predicted gradual release of GHGs over extended period [8, 9]. Process emissions category in Scope 1 covers the direct GHGs released through industrial processes and on-site manufacturing e.g., GHGs generated during chemical manufacturing [8, 9] .

Scope 2 of Greenhouse Gas Protocol (2022) quantifies indirect emissions related to the acquirement and consumption of electricity, steam, heat or cooling [10]. These emissions are included in the reporting organization’s GHG inventory as they are a result of the actions of

the reporting organization, yet the physical emissions occur at sites owned or controlled by another organization [10]. Scope 2 includes exclusively indirect emissions from energy generation as other remaining upstream emissions linked with the production and refinement of upstream fuels, transmission or supplying energy within a grid, are accounted for in Scope 3, category 3 [10, 11]. Generally, Scope 2 emissions are one of the largest GHG emission sources globally as the production of electricity and heat represents no less than a third of global GHG emissions [10].

Scope 3 emissions comprise of all sources of organization's indirect emissions not included in Scope 2 boundary [11, 12]. These scope boundaries are not completely fixed in the sense that, for some organization's Scope 3 emissions are the scope 1 and 2 emissions for another organization and vice versa [12]. Scope 3 emissions are frequently referred to as value chain emissions and they most often account for the majority of GHG emissions within an organization [11]. Although Scope 3 emissions are not under the direct supervision of the reporting organization, organizations may influence which suppliers or vendors they choose and thus influence the amount of Scope 3 emission generated by the reporting organization [12].

Value chain emissions can be divided into two categories: upstream activities and downstream activities (Table 1) [11, 12]. In Scope 3, the upstream activities represent material acquisition and pre-processing, including but not limited to capital goods, fuel and energy related activities, waste generated in operations and purchased goods and services [12]. Downstream activities in Scope 3 are about the distribution and storage, use and processing of products, and end-of-life treatment of sold products [12]. Additionally, the downstream activities include investments and franchises [11, 12]. Some activities like leased assets and transportation and distribution are included in both upstream and downstream activities [11, 12].

The GHG Protocol has defined 15 categories (Table 1) within Scope 3 emissions, however not all categories apply to all organizations [12]. The categories were designed to guide companies with to facilitate organized and diverse reporting of Scope 3 activities within existing value chains [12]. The categories are mutually exclusive to prevent double counting of emissions within the reporting company [12].

Table 1 GHG Protocol Scope 3 categories divided by upstream and downstream emissions [12].

	Scope 3 Category
Upstream Scope 3 Emissions	1. Purchased goods and services 2. Capital Goods 3. Fuel- and energy-related activities (not included in Scope 1 or 2) 4. Upstream transportation and distribution 5. Waste generated in operations 6. Business travel 7. Employee commuting 8. Upstream leased assets
Downstream Scope 3 Emissions	9. Downstream transportation and distribution 10. Processing of sold products 11. Use of sold products 12. End-of-life treatment of distributed products 13. Downstream leased assets 14. Franchises 15. Investments

The Corporate Value Chain (Scope 3) Standard has defined the minimum boundaries of each category with the intention to create standardized categories and to provide clear guidance for organizations to follow [12]. The standardization of Scope 3 categories guarantees that all significant activities are included in the emission inventory [12]. In the case of categories 1— 3, the minimum boundaries cover all upstream emissions (cradle-to-gate approach) which guarantees that the organization's emissions inventory includes the GHG emissions of purchased products wherever they take place within the life cycle [12]. In this context the life cycle refers to the sequence of change from raw material extraction to the purchasing done by the reporting company [12].

In most cases (excluding categories 1-3, Table 1), the category's minimum boundary encompasses the Scope 1 and 2 emissions generated by the relevant value chain partner such as waste management company, transportation provider or carrier, franchisor or consumer [12]. This means that most of emissions associated with Scope 3 categories are a consequence of activities of the entity as opposed to emission related to manufacturing products or infrastructure [12]. In addition, to defining the 15 emission categories and their minimum

boundaries, the Scope 3 emissions standard also establishes a time boundary (Table 2) for each category to ensure consistency, accuracy and comparability in reporting [12]. The use of time boundaries helps to ensure that emission sources are not double counted nor are they overlapping [12].

Table 2 Time boundary of scope 3 categories [12].

Past Years	Reporting Year	Future Years
1.Purchased goods and services	1.Purchased goods and services	
2.Capital Goods	2.Capital Goods	
3.Fuel- and energy-related activities	3.Fuel- and energy-related activities	
4. Upstream transportation and distribution	4.Upstream transportation and distribution	
	5.Waste generated in operations	5.Waste generated in operations
	6.Business travel	
	7.Employee commuting	
	8.Upstream leased assets	
	9.Downstream transportation and distribution	9.Downstream transportation and distribution
	10.Processing of sold products	10.Processing of sold products
	11.Use of sold products	11.Use of sold products
	12.End-of-life treatment of sold products	12.End-of-life treatment of sold products
	13.Downstream leased assets	
	14.Franchises	
	15.Investments	15.Investments

2.4 Global emissions caused the healthcare sector

As previously mentioned in chapter 2.1, the healthcare sector contributes 4.4% of net emissions (equivalent of 2 gigatons of CO_2) globally and so far, the sector's carbon footprint has only been increasing with each passing year due to the growing need for energy, transportation and manufacturing [4, 5]. The majority of the emissions (71%) for the

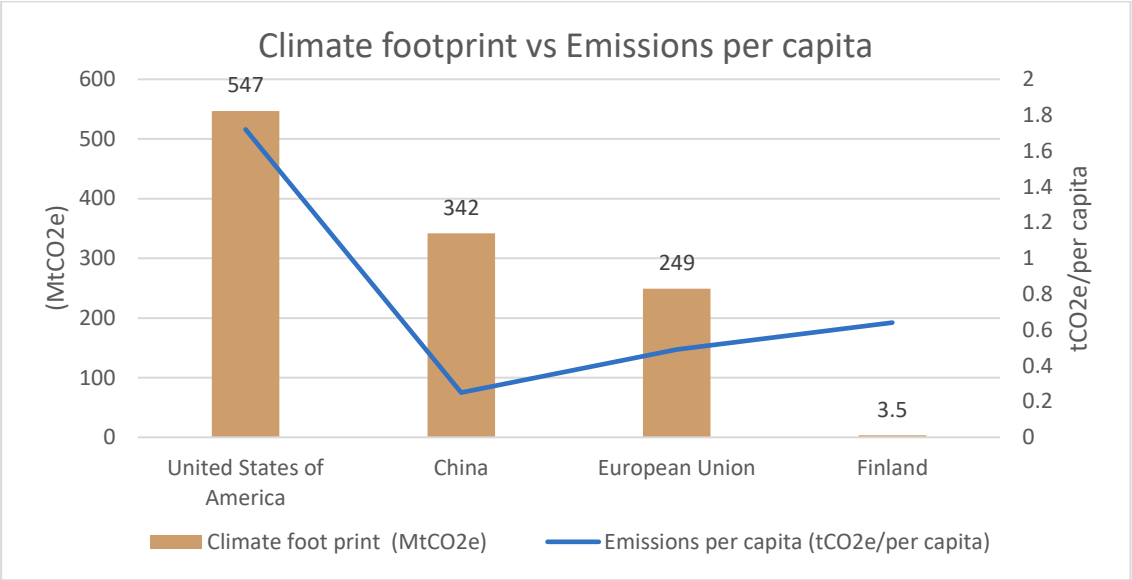
healthcare sector are derived from its supply chain (Scope 3) via manufacturing, transportation and distribution of goods and services including pharmaceuticals and other relevant chemicals, medical devices, instruments and hospital equipment [5].

Additionally, studies have found that 3-quarters of all generated emissions within healthcare are generated domestically, and one-quarter of emissions are produced outside of the country where the product is used [5]. While Scope 3 emissions represent the majority of the healthcare sector's emissions, the impacts of Scope 1 and 2 emissions should not be diminished as they account for 17% and 12% of the sector's worldwide emissions [5]. When reviewing the biggest emissions sources across all the scopes, it is noticeable that energy, specifically fossil fuel combustion, accounts for more than half of healthcare sector's emissions [4, 5].

According to a report published in 2021 by the nongovernmental organization Health Care Without Harm, there is a strong but not absolute correlation between a country's GDP, healthcare spending and healthcare sector's climate footprint [4]. Countries with higher GDP usually contribute higher spending towards healthcare services and thus they exhibit a higher per capita healthcare emission when compared to countries with lower GDP [4]. Other major components which affect the climate footprint in this case are the energy intensity of a country as well as the emission intensity of its energy system [4].

The European Union, consisting of 28 nations, accounts for 12% of the absolute emissions (249 megatons of carbon dioxide equivalent [$MtCO_2e$]) in healthcare and has an average of 0.49 tCO_2e per capita which places the Union in higher-than-average emitters category (global average of 0.28t — 0.50t per capita) [4]. However, within the union, the 28 countries have a plethora of variation with their emissions per capita value and most of the countries fall into the higher-than-average emitters or major emitters (0.50t —1t per capita) category [4]. Only 6 countries within the European Union are placed within the lower-than-average emitters category (< 0.28 tCO_2e.) [4].

Table 3 Climate footprint vs Emissions per capita comparison [4].



Scope 3 emissions rank as the highest percentage emission category for The European Union with 75% while Scope 1 and 2 emission account for 14% and 11% respectively [4]. These distribution percentages between different Scopes are very in line with the global average [4].

Finland has a healthcare climate footprint of 3.5 $MtCO_2e$ and produces 0.65 tCO_2e per capita, meaning the country is categorized as higher-than-average emitter and produces more emissions when compared to the European Union Average tCO_2e per capita (Table 3) [13]. Healthcare emissions account for 5% of Finland's national climate footprint and only 48.4% of this footprint is generated domestically, meaning that majority of Finland's emissions are produced outside the country which directly reflects in the Scope 3 emissions [13, 14]. 82% of all healthcare emissions of Finland belong in Scope 3 and this is above the global and European Union average percentage for Scope 3 emissions [13]. Scope 1 and 2 emissions make up only 5.5% and 13% of Finland's healthcare emissions [13, 14]. Most emissions generated within Finnish healthcare can be traced to medicine and medicine raw materials, nutrition services and food as well as electricity and heat / cooling systems [14]. Anaesthesia gases accounts for very little in terms of percentage of Finland's emissions however these gases are equal to fluorinated gases, making their impact thousand-fold when compared to CO_2 [14].

3 Standards and regulations guiding sustainability

Standards and regulations provide established procedures, requirements and guidelines in steering industries towards more sustainable practices while simultaneously ensuring consistency, safety and quality of health technologies. While both standards and regulations guide the industry, standards are usually industry driven, voluntarily implemented by companies and developed by various organizations. In contrast, regulations are mandatory and legally enforceable by either national or international authorities. Conjointly standards and regulations form a complementary framework that encourages innovation while keeping accountability in high regard [15]. Regulations set the baseline requirements to ensure safety, environmental protection and ethical integrity, while standards usually include and expand more than just the baseline requirements [16]. Many times, standards make compliance with regulation more convenient since standards provide more detailed practices and methods than regulations [15, 16]. ISO (International Organization for Standardization) is one of the most influential non-governmental international organizations, which consists of national standards bodies from 174 countries [16]. The aim of ISO is to create standardization across various products, companies and industries, while simultaneously promoting trade, process improvements, quality and safety [16].

3.1 ISO 14001 environmental management systems (EMS)

International standard 14001 outlines the requirements for environmental management systems (EMS) and cover topics such as leadership, planning, support, operations, performance evaluation and improvement [15, 17]. The standard defines the general requirements and procedures, however it’s also nonprescriptive, meaning that it explains what should be accomplished but not how to achieve it [17]. If the standard guidelines are abided by the implementing organization, it should yield suitable assurance that any output from the systems should have a minimal negative impact on the environment while at the same time improving environmental performance [17]. ISO 14001 assists organizations to improve resource efficiency, manage costs and reduce excess waste, increase business opportunities through enhanced brand reputation and trust while at the same time making it more effortless to meet the legal obligations [15, 18].

3.2 ISO 14040/14044: Standards for Life Cycle Assessment (LCA)

The ISO standards 14040 and 14044 form the framework and requirements for Life Cycle Assessment (LCA) [19]. The LCA was designed to help identify environmental performance improvement possibilities of products at any point within its lifecycle, enabling informed decision-making regarding priority setting, strategic planning or process redesign [19]. Additionally, LCA helps in choosing relevant indicators for environmental performance and how all the previously mentioned aspects can be utilized in marketing and creating company trust [19]. Assessing environmental performance through LCA assures that other environmental factors than just CO_2 are considered during environmental decision making, putting emphasis to cradle-to-grave thinking [19]. The combination of standard 14040 and 14044 makes sure that each of the significant phase (raw material and extraction, production and manufacturing, distribution, use and end-of-life) of the product is closely considered [19, 20]. Standard ISO 14040 includes the principles, framework and stages of LCA while ISO 14044 includes the detailed requirements and methodology [19, 20].

The LCA is considered to include four distinct phases: goal and scope definition, life cycle inventory analysis phase (LCI), life cycle impact assessment phase (LCIA) and lastly Life cycle interpretation [20]. The second phase, LCI, is about making an inventory of the input and output data within the scope of the system being assessed [20]. The objective of this phase is to collect enough relevant data to achieve the goals set for the study. In the third phase, LCIA, the data gathered in LCI is evaluated with the aim of producing additional information to assist in the evaluation of system's environment impact like acidification, eutrophication, ecotoxicity or ozone depletion [20, 21].

ISO 14044 methodologies for LCA applications can be expressed with three categories: bottom-up life cycle assessment, top-down cycle assessment also known as economic input-output analysis and lastly a hybrid or combination model of both previous models [22]. In the bottom-up LCA methodology, all the materials utilized in manufacturing process of a product are first quantified after which each required material or item is multiplied in accordance with a conversion factor [22]. In contrast, the top-down cycle assessment (economic input–output analysis) puts emphasis on the money used in a manufacturing process or a product and multiplies it the amount with a conversion factor [22]. As the name suggests, the hybrid model LCA utilized both economic input–output analysis and material quantification methodology used in bottom-up LCA [22].

3.3 Health Technology Assessment (HTA Regulation (EU) 2021/2282)

The European Union regulation 2021/2282 on Health Technology Assessment (HTA) was put in effect on 11th of January 2022 and applying it became mandatory starting from 12th of January 2025 [23, 24]. HTA was created to improve collaboration between the EU member states, enable evidence-based decision making, make the assessment process more efficient and to promote accessibility and innovation in health technologies sector [23, 24]. The HTA regulation is not meant to only address the technical parts of health technologies, but it also considers other aspects of sustainability such as ethical, economical and socials issues [23, 24]. The HTA regulation defines that health technologies category includes but is not limited to medicinal products, diagnostics equipment and consumables and medical equipment meant for treatment or prevention purposes [23, 24].

Essentially due to the regulation, health technology assessment bodies need to evaluate new technology in such a way that they consider whether the technology functions worse, equally well or better than the current alternatives [21]. In the case of medicinal products like drugs, the HTA bodies need to consider the therapeutic effects that the drug might have, and in addition consider the possible side-effects, how the drug is administrated as well as how the quality of life is affected through the use of such drug [21]. Furthermore, to achieve a multidisciplinary systematic review, other aspects like cost implications for patients and healthcare systems need to be taken into an account as well as the impacts on the healthcare organization providing the treatment or technology [21]. The correct implementation of HTA regulation helps to streamline HTA processes by reducing duplicate assessments done by HTA authorities and health technology industry, creates business reliability and facilities continued efforts towards sustainability and EU level cooperation [24, 25].

4 Natural organic polymers used healthcare applications

Biodegradable and biocompatible materials address multiple issues faced in non-invasive and invasive health monitoring. These materials can be manufactured from abundant and renewable green materials which often exhibit intrinsic biocompatibility and biodegradability. Due to the biodegradable features, extraction or reoperation steps on the patient are eliminated, which in turn aids to minimize any inflammatory responses and reduces costs associated with patient care. Additionally, less medical and electronic waste would be produced during patient care, which would positively contribute to reducing carbon footprint and Scope 3 measurements of the healthcare facilities.

The biodegradable materials used in health monitoring applications can roughly be divided into 5 categories: encapsulants and adhesives, substrates, electrodes, semiconductors and dielectrics [26]. Depending on the category of materials, the devices could be used to monitor wound and tissue healing, skin and brain temperature, pressure in blood, brain and lungs or to monitor glucose, dopamine or ion levels [26]. Due to research and development, critical device components such as dielectric and active layers, interconnects, conductive contacts and substrate materials, can be manufactured from low-cost, safe and disposable materials like biodegradable polymers (natural, synthetic or conjugated), hydrolysable metals or either organic or inorganic semiconductors (Figure 1) [26].

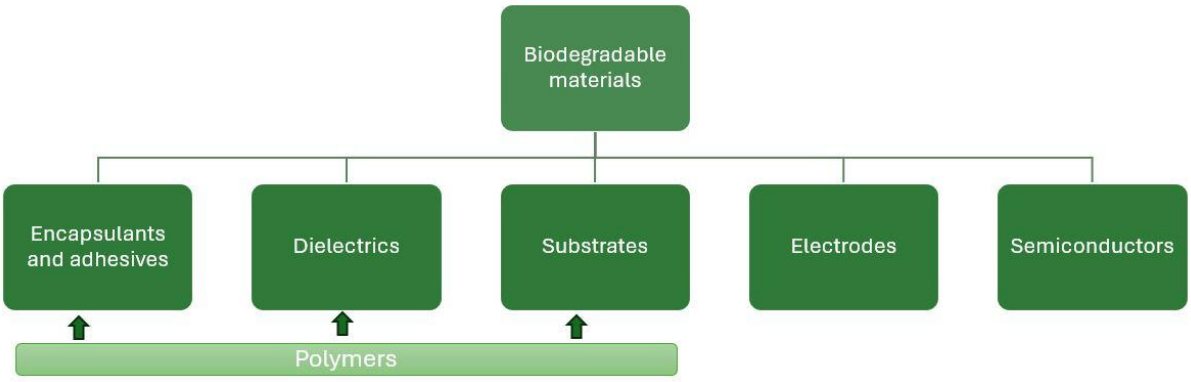


Figure 1 Categories of biodegradable materials used in health monitoring devices.

Polymers are highly attractive option for customizable and biodegradable device components since many of their attributes like morphology, chemical structure and dissolution time scale can be specifically tailored by modifying material properties such as chemical composition, crystal structure, erosion mechanisms, hydrophilic or hydrophobic nature and molecular weight [26]. Organic, protein-based polymers like collagen, gelatine, silk, fibrin and chitosan

have found their place in device manufacturing due to their bioactive ability, which can be traced back to their similarity with biological macromolecules [26]. This similarity between protein-based polymers and biological macromolecules enables immunogenic response, which can be greatly beneficial at invasive healthcare applications. However, the overall applications of organic polymers are greatly restricted by their inherent flaws such as weak mechanical properties, high batch variation and structural complexity [26]. Plant-based polysaccharides like starch, dextran, alginate and cellulose share similar qualities with protein-based materials and as such their applications are limited by same hinderances [26].

The following chapters introduce the natural organic polymers collagen, chitosan and alginate, including their properties, characteristics and a few of their applications in health monitoring purposes. Collagen, chitosan and alginate have been extensively researched for health technology purposes in the past and through that it has been established that they offer relatively good balance of characteristics such as biodegradability, non-toxicity, biocompatibility.

Table 4 Renewability and valorization of natural organic polymers.

Material	Sources	Renewability / biodegradability	Challenges?	Valorization potential
Collagen	Bovine, marine, recombinant	Slow / Yes	Zoonosis diseases Allergic reactions Religious concerns	Industrial waste / by-products (dairy, meat, leather and fishing).
Chitosan	Invertebrate, insects, fungi	Slow (invertebrate) to fast /Yes	Pathogens Overfishing Solubility of chitosan	Fish waste, insect and fungi farming.
Alginate	Brown algae	Fast / Yes	Toxic chemical solvents in manufacturing	Naturally available in the ocean and longstanding cultural traditions.

Collagen, chitosan and alginate can be derived from multiple sidestream sources (Table 4), either on land or water environments and thus the material practices could be considered sustainable, however by utilizing industry by-products, the health technology industry makes its material production dependent on continuous animal consumption as well as fishing which can impact environments negatively through overfishing. For sustainability purposes, it's important and beneficial that health technology industry starts to apply previously neglected by-products, however it's important that the materials are indeed by-products and do not become the main product for which the material sources such as cattle and crustaceans and harvested for.

4.1 Collagen

Collagen is one of the most abundant materials present in the extracellular matrix (ECM), which creates signals for cell regulations and tissue morphogenesis in addition to giving structural support and integrity to sustain the three-dimensional (3D) shape and stability of a biological tissue [27]. Collagen is especially known for its triple helical structure (Figure 2), outstanding biocompatibility, low antigenicity and for its abundance in vertebrate organism [28]. The triple helical structure and its composition is used as a differentiating factor for the identification of various types of collagens [29].

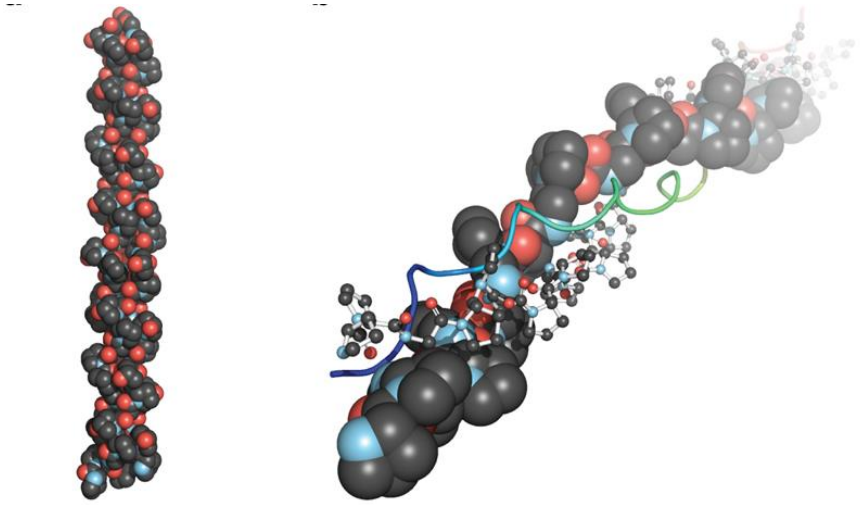


Figure 2 The structure of collagen triple helix. Images reproduced with permission. [29] Copyright 2009, Raines Ronald T. and Shoulders Matthew D.

28 different collagen types have been identified based on the collagen's triple helical structure composition, however types I – V are the most common variants [29]. Additionally, collagens can be categorized as classical fibrillar and networking collagens or as non-fibrillar collagens [29]. Non-fibrillar collagen categories include MACITs (membrane-associated collagens with

interrupted triple helices), FACITs (fibril-associated collagens with interrupted triple helices), and MULTIPLEXINs (multiple triple-helix domains and interruptions) [29].

Type I collagen is the most abundant collagen present in the human body, and it is widely spread within the body in dermis, bone, tendon and ligaments [29]. Type I is relatively densely packed fibrillar collagen and as such it provides structure in its applications [29]. In comparison to type I collagen, type II fibrillar collagen forms thinner fibrils and provides elasticity in cartilage and vitreous [29]. Type III fibrillar collagen can be found in skin, blood vessels and intestines, where it provides structural support alongside elasticity. [29] Type IV collagen forms networks instead of fibrils and functions as a key component in basement membranes located in kidneys, lungs and blood vessels [29]. Basement membranes bear great significance in producing physical and chemical cues for the overlaying cells [29]. Type V collagen is fibrillar and it is widely spread within the body in bone dermis, cornea and placenta [29]. Type V collagen bears great significance for the fibrillation of type I and III collagen and therefore affects significantly the optimal fibrillary formation and tissue quality [29].

Many of the collagen types can be tied to various medical syndromes or disorders. For example, Ehlers-Danlos Syndrome (EDS), where collagen fibril formation and function are compromised, can be linked to type I, III and V collagens [29, 30]. The syndrome often manifests with hypermobility of joints, fragility of blood vessels and skin hyperelasticity [29, 30].

Overall, collagen possesses useful characteristics like cell adhesion, drug compatibility and cellular process regulation such as proliferation, differentiation and migration which is why they are most often utilized in medical therapies related to regenerative medicine (bone substitute, wound dressings and artificial blood vessels) and drug delivery systems [27, 28]. Most commonly collagen is used in hydrogel, fibre and membrane form to capitalize their full potential in biomedical applications like muscle loss and lymphatic regeneration [28]. In the applications related to bone substitutions, utilization of type II collagen is crucial as it represents the most important structural element present in ECM of articular cartilage [28]. As mentioned previously, applications of biopolymers can often be limited due to their characteristic hinderances like thermal instability and lacking mechanical strength. Some of these negative drawbacks can be negated with the addition of cross-linking agents, inorganic fillers or synthetic polymers [28].

4.1.1 Collagen hydrogels in wound dressings

Collagen-based hydrogels have been demonstrated to function extremely efficiently in wound dressing applications due to collagen's ability to form fibres spontaneously in aqueous environments when conditions for concentration, pH and temperature are met [31]. The formation of collagen-based hydrogels is entirely reliant on this self-assembly mechanism [31]. Typically, collagen-based hydrogels are divided into three categories based on the material which collagen is mixed with. The first category of hydrogels consisting only of pure collagen however, they can be modified with the addition of therapeutic agents for improved biological responses. The addition of bioactive chemicals to collagen hydrogels can in certain cases cause hazardous responses, though the inclination can be minimized by using them only with pure collagen [32].

The second category includes organic collagen mixed with other polymers such as chitosan, hyaluronic acid (HA) and sodium alginate [22, 32]. Hyaluronic acid is one of the main components of ECM and it plays an important role during the wound healing process in cell proliferation, migration and tissue remodelling [32]. HA is a linear non-sulphated glycosaminoglycan (GAG) which forms non-covalent bonds with aggrecan [33]. The polymer is especially noted for its ability to retain up to 1000 times its weight in water and high viscosity [33]. High molecular weight HA (>1000 kilodaltons) particularly affects homeostasis, wound healing and anti-inflammatory responses while low molecular weight HA (10-250 kilodaltons) engages macrophages and proinflammatory responses [33]. The wound healing induced by collagen and HA hydrogels is the result of their interaction with cell surface receptors which then promotes matrix remodelling including synthesis of new molecules and generation of degrading enzymes [33]. HA is considered to have low cell adhesion potential due to its hydrophilic nature but despite that, it has been noted that HA works efficiently in prevention of glial scar development [34].

The third category covers the collagen blends with bioactive materials [22]. Bioactive agents such as antibiotics, plant extracts, microbes, metal nanoparticles (e.g., copper or silver) or growth factors can be introduced into collagen blends to enhance the hydrogel's properties or drug delivering capabilities [32]. Introducing functionalized nanoparticles to collagen blends helps to strengthen and stabilize collagen tissues and metal oxides particularly have been used to fortify mechanical characteristics of collagen-based scaffolds [32]. The metal nanoparticles

crosslink collagen by directly attaching to the collagen's sidechain [32]. In addition to providing strength and stability, the metal nanoparticles reduce inflammation and add multiple antibacterial properties into the collagen blends. The addition of metal nanoparticles to hydrogel wound dressing can be utilized to combat the infection caused by drug-resistant bacteria and slow wound healing rate [32].

The blending of collagen with other materials has created diversity in the material composition of the wound dressings available in the healthcare market. Some notable tradition collagen-based wound dressings include 3M™ Fibracol™ (90% collagen and 10% alginate), MatriDerm® (bovine collagen I,III, V and elastin) and Integra® Wound Matrix (bovine collagen and chondroitin-6-sulfate matrix) [22, 35, 36, 37]. They are widely used for burn wounds (reconstructive and acute), diabetic foot ulcers as well as in reconstructive cancer excisions [22, 35].

Smart wound dressings were developed to combat the pitfalls of traditional wound dressing by providing real-time monitoring of wound healing biomarkers, enabling early infection and inflammation diagnosis as well as on-demand treatment of these adverse reactions [38]. Smart wound dressing often includes integrated systems for drug delivery, wearable sensors and as well as option for wireless communication for monitoring purposes [38]. Continuous monitoring of biomarkers such as temperature, moisture and pH, in combination with monitoring of enzymes, metabolites, bacteria and signalling molecules aids in identifying how well the wound is healing or if there is any deterioration occurring [38]. On-demand treatment of wounds through intelligent drug delivery have garnered plenty of attention as of late due to the significant improvements in wound healing rates [38]. The drug release mechanism in the wound dressing would be responsive to the physiological changes occurring in the wound environment and based on pH, temperature, glucose or enzyme levels, bioactive drug factors would be released to encourage wound healing [38]. The drug release mechanisms can be mono-, dual-, or multi-responsive [38].

4.1.2 Collagen as a substrate candidate in bioelectronics

Collagen has multiple favourable properties which have been proven useful for bioelectronics substrate applications, especially in implantable electronics uses [39]. Substrates used in implantable electronics ought to have mechanical properties akin to the implant target tissues

as well as be biocompatible [39]. Silk and cellulose have in the past been more explored for implantable bioelectronics, however recently collagen has gained momentum in the types of applications as many of its functions in regard to cell adhesion, migration and proliferation are superior to silk and cellulose [39].

Many of collagen's inherent characteristics are greatly beneficial in high-performance flexible sensor applications since the sensors require materials which are able to interact and conform to curved surfaces of biological systems with variety of small surface deformations [40]. Furthermore, collagen has multiple unique reactive functional groups, such as -OH, -COOH and NH_2, available on its molecular chain, which promotes additional modifications and thus facilitating further optimization of the functionality of flexible sensors [40].

Collagen has already been utilized in long-term implants, namely in heart valves, cell scaffolds and pericardial patches [39]. The previous successful application of collagen in long-term implants has greatly reduced the concern for adverse reactions such as strong immune response or foreign body response (FBR), making collagen a promising option for bioelectronics [39]. It is crucial to note that lower collagen density offers better biocompatibility and reduces the risks of FBR in bioelectronics applications [41]. Among bioelectronics, flexible and wearable bionic electronic skin (e-skin) has gained attention as it combines multiple monitoring functions for biological signals, external environmental monitoring and mechanical deformation in the same device [42]. E-skin can be applied to health monitoring, medical diagnosis and rehabilitation among many other applications [42]. In the past e-skin has been limited by the material choices, usually metal or semiconductors, which have rendered the device incompatible with human skin, however conductive hydrogels made from collagen have begun to replace these materials [42]. Typically, hydrogel-based e-skin functioning as a sensor utilizes only a strain resistance-response for the monitoring of biological signals (small and large human motions) and thus the data is only acquired through a single source [42]. Utilizing e-skin in health monitoring applications, specifically for monitoring of motions, allows real-time monitoring and continuous feedback which can be beneficial for injury and surgery rehabilitation as well as for the detection of abnormal motion patterns which can be used for early detection of Parkinson's disease [43].

4.2 Chitin and chitosan

Chitin is an abundantly available organic polymer comprised of 1-4 glycosidic bonds as well as N-acetyl D-glucosamine monomers [44, 45]. The compound can be acquired from multiple organisms including certain algae (coralline, green and brown), fungi, bacteria and exoskeletons of invertebrates such as insects, crustaceans and molluscs [44]. In recent years chitin has been recognized for its multiple useful properties for healthcare applications, namely for tissue engineering, drug delivery, cancer therapy and wound healing. Due to chitin's molecular composition, the material is inherently biodegradable, nontoxic, biocompatible and can be enzymatically degraded [44, 45]. Traditionally, the use of chitin has been hindered by its semi-crystalline structure and extensive intermolecular hydrogen bonds, rendering the compound insoluble in most commonly used solvents [44]. Chitin has three formally recognized crystalline allomorphs, α–, β– and γ–type which are differentiated based on which direction the polymer chains are oriented towards (Figure 3) [46]. α-type is the most stable allomorph of chitin found mostly in crustacean shells and the polymer chains are joined antiparallel [46]. β-type chitin is mainly available from squid pens, the polymer chain lay parallel and are connected by intra sheet hydrogen bonds [46]. γ-type is the scarcest chitin allomorph available, and its structure consists of two parallel polymer chains with one anti-parallel chain [46].

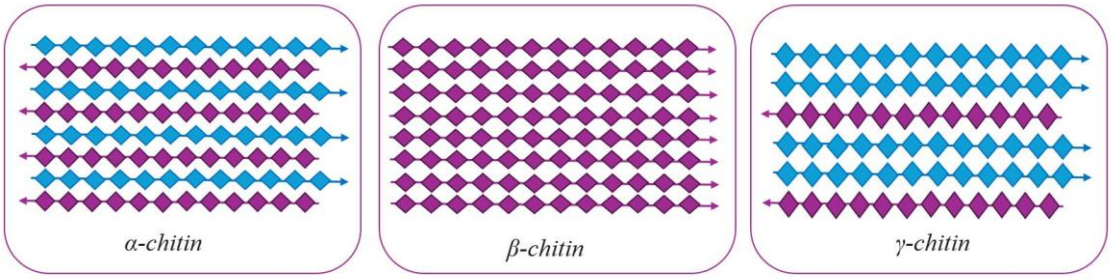


Figure 3 Chitin α–, β– and γ–type allomorphs (adapted from [41]).

Due to recent advances made in material manufacturing technologies, the partial N-deacetylation of chitin can be modified into chitosan which is a soluble substance [44]. Chitosan is derived from chitin through deacetylation process performed in strong alkaline solution causing the chitosan to dissolve into the acidic environment [44, 45]. The derived polymer exhibits various practical properties including but not limited to metal chelation, biocompatibility, antimicrobial, gel-forming and antioxidant [45]. The extent of these

properties is influenced by the allomorph type from which chitosan is derived from as it has been noted that *β*-allomorphs of chitosan have better fat and water binding capabilities, and they are more solubility than chitosan derived from α-type chitin [46]. Furthermore, *β*-allomorph derived chitosan is more porous and exhibits notably superior pharmacological characteristics such as antioxidant as well as anti-inflammatory activities than α -allomorph derived chitosan [46]. Chitosan is relatively easy to process once it's derived from chitin, making the polymer more attractive to health technology industry applications due to large scale manufacturing being more attainable [45]. Regarding chitosan applications in health technologies, the most traditional use for chitosan is for the fabrication of homeostatic agents used in wound treatment, however other medical applications for chitosan are being developed, for example use of chitosan derivates for non-viral gene delivery vectors, diagnostics and regenerative medicine [45, 47].

Chitosan is one of the few naturally occurring polycations, meaning it has multiple positive electrical charges along its molecular chain [48]. The charge density within chitosan can be influenced through pH of the media as well as by the degree of acetylation [48]. The combination of molecular weight and acetylation determines how soluble chitosan is in the media [48]. Despite high deacetylation degrees, heavy molecular weight chitosan specimens can be dissolved solely in acidic aqueous solutions while the oligomers can be dissolved in both basic and acidic media [48]. Chitosan's strict requirements regarding its solubility have made it challenging to apply the polymer in a wide range of healthcare applications, especially those utilized under neutral pH conditions [48]. Despite the issues associated with chitosan's solubility, the polymer possesses a relatively stable chemical structure which facilitates biocompatibility with multiple types of tissues, cells and organs [47].

4.2.1 Electrochemical sensors for pharmaceutical detection

The monitoring of pharmaceutical substances in matrices provides additional means of making certain that medication therapies are administered in appropriate amounts and that the quality of pharmaceuticals are up to standards [49]. Electrochemical sensors used in pharmaceutical detection are intended to be used in combination with traditional techniques like mass spectrometry and liquid chromatography as electrochemical sensors offer rapid analysis and affordability, but they are also hindered by reproducibility and long-term stability [49]. In general, electrochemical sensors have many favourable attributes including high sensitivity, real-time monitoring potential and high sensitivity. In addition to the previously

mentioned properties, electrochemical sensors have intrinsic benefits in regard to size miniaturization and portability [49]. The application of chitosan in electrochemical purposes has been researched considerably due to the favourable material properties like large contact surface area, biodegradability and biocompatibility [49]. Furthermore, chitosan showcases great potential as electrochemical sensor material since it can be effortlessly functionalized and modified for enhanced properties [49]. Other nanomaterials, for example metal or carbon-based, can be utilized in chitosan modification to gain better transfer rate, stability, sensor selectivity or selectivity [49]. Other conductive polymers can also be utilized to enhance chitosan's performance in electrochemical sensor applications [49].

Hydrogel sensors are commonly utilized in smart wearable devices due to their flexibility, stretchability and self-adhesive properties which enables the continuous contact between skin and hydrogel sensor [50]. The addition of chitosan in these kinds of applications helps to create beneficial construction within hydrogels that enable greater adhesion [50]. Flexible wearable devices facilitate remote personalized health monitoring of multiple aspects such as pulse, motion, biochemical parameters and temperature [51].

Chitosan based sensors can be utilized to detect a variety of pharmaceutical substances ranging from antiallergic substances to even narcotics [49]. Among antiallergic substances, cetirizine, phenylephrine, dextromethorphan and chlorpheniramine maleate are few of the most successfully detected substances due to the common occurrence of allergic diseases [49]. Chitosan based aptasensors have also demonstrated their usefulness in early disease detection by identifying neoplastic markers like epidermal growth factor receptor 2 proteins which are vital signs of breast cancer [49]. Other applications for electrochemical sensors are the detection of metabolites such as cholesterol and uric acid as well as the quantification of popular pharmaceutical substances like paracetamol, propranolol and fluoxetine [49]. As chitosan based electrochemical sensors are able to identify narcotic substances such as methamphetamine, cocaine and morphine, they can be used in healthcare to avoid misdiagnosis and dangerous medication combinations to provide patients with more effective treatment [49].

4.2.2 Humidity sensors for human health monitoring

Humidity sensors can be applied for various purposes in healthcare ranging from detection of contagious diseases like SARS and Covid-19 to endocrine disorders such as diabetes and thyroid conditions [52]. Respiratory function is a core indicator for human health and monitoring respiratory humidity offers a non-invasive, economic, highly sensitive and comfortable option for health detection [52]. Common manufacturing materials for humidity sensors are porous ceramics, polymeric materials as well as semiconductors, however polymers are one of the most utilized materials due to great characteristics including biocompatibility, non-toxicity and chemical inertness [52]. Among polymers, chitosan is particularly popular in humidity sensor applications because of its affinity for water molecules which is based on the interactions of water molecules with repeated functional groups such as amine and hydroxyl through hydrogen bonds [52].

Majority of the research has been conducted on optical based techniques, mainly Fabry–Perot interferometers, fiber Bragg grating and quartz crystal microbalances (QCM), which suffer from high fabrication costs and complex detection techniques which limits the commercialization opportunities [52]. Alternatively, resistance-based measurements have started to emerge as they are fairly uncomplicated to manufacture and assemble, making resistance-based humidity sensors a more economically efficient option [52]. QCM, resistance and colorimetric-based sensors represent the majority of researched humidity sensors for health monitoring, however recently it has been noted that chitosan also exhibits advantageous capacitive properties and capacitive-based humidity sensors are an area of future interest [53]. Chitosan based sensors can be manufactured with techniques such as film casting and drop-casting [52].

4.3 Alginate

Alginate is an anionic and hydrophilic polymer which is primarily derived from brown algae and in some cases from selected soil bacteria [54, 55]. For brown algae, alginate is the predominant matricial polysaccharide, however majority of brown algae do not carry sufficient amounts of alginate to provide materials for industrial applications [54].

Alginates are composed of linked β-D-mannuronic (M) and α-L-guluronic (G) acids in pyranosic form, and they can be organized into homogeneous (MM or GG) and

heterogeneous (MG or GM) blocks [54]. The difference in structural arrangements facilitates a great variety of molecular weights, structures as well as physiochemical properties [54]. Alginate has been noted for its many useful properties including regenerability, nontoxicity, biocompatibility and inert nature [56].

Majority of commercial alginates are derived from brown algae species such as *Laminaria hyperborea, Saccharina japonica*, *Laminaria digitata, Ascophyllum nodosum* and *Macrocystis pyrifera* [54, 57]. The composition, abundance and M/G ratio of alginates is strongly dependent on the algae species and age, geographical location and season [54]. The previously mentioned aspects influence the key functional characteristics such as reactions with metal ions, gel formation, solubility as well as viscosity [54]. Algae growing in hot climate produces alginate which can be used in biomedical applications to form strong gels, while alginate derived from cold climate algae usually have a poor viscosity [54].
One of the key factors affecting the formation of hydrogels is the G-block content of the alginate as G-blocks mainly part take in the intermolecular crosslinking in combination with divalent cations [55]. While G-blocks are essential for hydrogel formation, M-blocks contribute to immunogenicity and induce stronger cytokine production [55]. Alginate produced through commercial processes commonly has a molecular weight between 32 000 – 400 000 grams per mol [55]. High molecular weight alginate offers better physical properties such as increased water retention and gel strength; however, it can cause issues with high viscosity and injectability [55].

4.3.1 Alginate hydrogels for sweat composition monitoring

Calcium crosslinked alginate (Ca-Alg) and barium (II) crosslinked alginate (Ba-Alg) hydrogels have especially been noted in recent years for biomedicine, biosensor and bioactuation purposes as they offer the possibility to combine hard artificial machinery with soft biological systems [58]. In conventional ionotropic hydrogel biosensors, the working mechanisms of the biosensor are based on the diffusion of analytes into the free volume of the hydrogel, where the following biomolecular binding is then transduced into a detectable signal [58]. Traditionally, enzymes execute biorecognition and the transduction is carried out by integrating responsive polymer or nanoparticles within the hydrogel forming composites [58] Alginate based biosensors are often utilized in the detection of lactate and glucose, as

enzymes such as glucose oxidase (GOx) and lactate oxidase (LOx) can be easily incorporated into the hydrogel where they act out as biorecognition elements [58].

Sweat composition monitoring offers a non-invasive way to detect a variety of compounds such as lactate, glucose, nitrogenous compounds, heavy metals, immune biomarkers, xenobiotics (narcotics, ethanol) and cortisol and stress biomarkers [59, 60]. Sweat is the primary means of thermoregulation of body, but it also protects and waterproofs skin, as well as functioning as a part of the immune system [59]. Sweat analysis can assist with measuring body dehydration and biomarker concentrations which can be utilized as a part of disease diagnosis, for example cystic fibrosis in which patients sweat carries increased amounts of chloride and sodium [59]. Lactate represents another high interest body compound as it is an important biomarker for fatigue and can signal oxygen levels being restricted since lactate is a product of the anaerobic metabolism occurring during high performance exercise [59].

Alginate-based hydrogel would be an appropriate choice for sweat composition sensor as it is a natural anionic polymer which is abundantly available from natural sources, and the material possesses many useful characteristics such as porosity, viscosity, gelation, non-immunogenicity and biocompatibility [59]. Traditionally, stability for prolonged periods has been one of the core challenges faced when the biosensor is formed from enzymes, however enzyme assays merged with alginate-based hydrogels can mitigate these constraints due to alginate's moisture retention and hydrogel's porous network which enables controlled diffusion [59].

4.3.2 Alginate-based bioactuators for smart drug delivery

Bioactuators are classified as materials which respond to stimuli such as pH, temperature, ultrasound or magnetic fields and their response to the stimuli causes an action like release of drugs [58]. Specifically soft actuators which are formed from soft matter and convert energy into motion, are becoming more popular in drug delivery and artificial muscle applications [58, 61]. Alginate hydrogels have inherent favourable properties for drug delivery such as high water content and porosity which enables encapsulation of large amount of payload as well as drugs including protein, antibodies and nanoparticles [58]. Due to the porous structure of alginate hydrogel matrix, the payload encapsulated into the hydrogel often diffuses uncontrollably, which can be observed by the initial burst followed by a gradual plateau [58].

The release mechanism of the payload is largely dependent on the isoelectric point of the payload and hydrodynamic radius [58]. To use bioactuators in “smart” drug delivery applications, the payload release mechanism should be only activated by external stimuli such as pH. Due to the inherent stability of alginate hydrogels, supplemental components such as enzymes or stimuli-responsive polymers should be incorporated to achieve “smart” actuation in response to stimuli [58].

Alginate-based hydrogels have been researched for cancer treatment purposes, and it has been noted that they have potential to improve to effectiveness of immunotherapy as well as chemotherapy [62]. Utilizing alginate hydrogels in cancer treatments enhances the selectivity and specificity of the drugs, while simultaneously reducing the systemic toxicity of drugs thus improving the anti-cancer activity [62]. Hydrogels utilized in cancer treatment can be engineered to respond to the stimuli generated by the tumour microenvironment such as pH, light and redox conditions and thereby enhancing the site-specific release of cargo [62]. These types of hydrogels usually include a monitoring option, for example in certain cases single-photon emission computerized tomography imaging can be utilized for monitoring purposes if there is an isotope labelling agent such as 125 I-labelled RGDY peptide present [62]. The application of alginate-based hydrogels have restrictions in cancer treatment as they require addition of adjunct materials such as contrast agents (gold nanoparticles or iron oxide) or fluorescent markers to achieve the required visibility for imaging modalities like fluorescence imaging, magnetic resonance imaging (MRI) or computed tomography (CT) [62]. As a result, it is crucial to integrate adjunct materials into hydrogels to enable real-time monitoring of drug release and biodistribution at tumour sites as well as to improve imaging accuracy [62]

5 Material sourcing, safety and environmental impact

Organic polymers can be sourced from various origins such as vertebrates, invertebrates or eukaryotes and they are often abundantly available due to their renewability and accessibility as by-products of numerous industries. One aspect of sustainability in health technology applications is the renewability of materials, however it is crucial to compare how the materials are derived from natural sources and whether they also fulfil the sociocultural and economic requirements set for sustainability.

Considering that the materials are applied to health technology applications, the safety of the materials is one of the key concerns. The safety of an organic polymer is conditional on where the said polymer is derived from and oftentimes the same compound has varying levels of risks associated with it depending on whether it's processed from vertebrates, invertebrates or eukaryotes. Risks between material sources can vary between allergic reactions to pathogen induced infections. In addition to material renewability, abundancy and safety, other environmental impacts such as deforestation, overfishing and greenhouse gas emissions need to be taken into consideration to have a systematic overview of sustainability.

5.1 Collagen

Type I collagen represents the most common collagen used in scientific applications due to the material's high availability and competitive costs [63]. Based on the recent market sales averages, collagen source price for health technology products should be within the 5000-50 000 USD/ kg to be commercially competitive option [64]. Animal sources like rat tail tendon, porcine and bovine skin-derived type I collagen are the most favoured in medical applications but alongside these, other alternatives derived from aquatic sources, human placenta or human skin derived collagen are available [63]. In the case of Type III collage, material sources vary from bovine to human placentas, skin derived from rat, chicken or human and in some cases marine-derived or recombinant sources applied (Figure 4) [63].

Animal sourced collagen accounts for the majority of used collagen in biomaterial applications as they are versatile in their use. However, the use of animal sourced collagen also includes possible negatives related to insufficient purification process, allergies and immunogenicity [63]. Insufficient or failed purification of collagen imposes the risk of

infectious disease transmission from animal to human. Insufficient or failed purification of collagen imposes the risk of infectious disease transmission from animal to human.

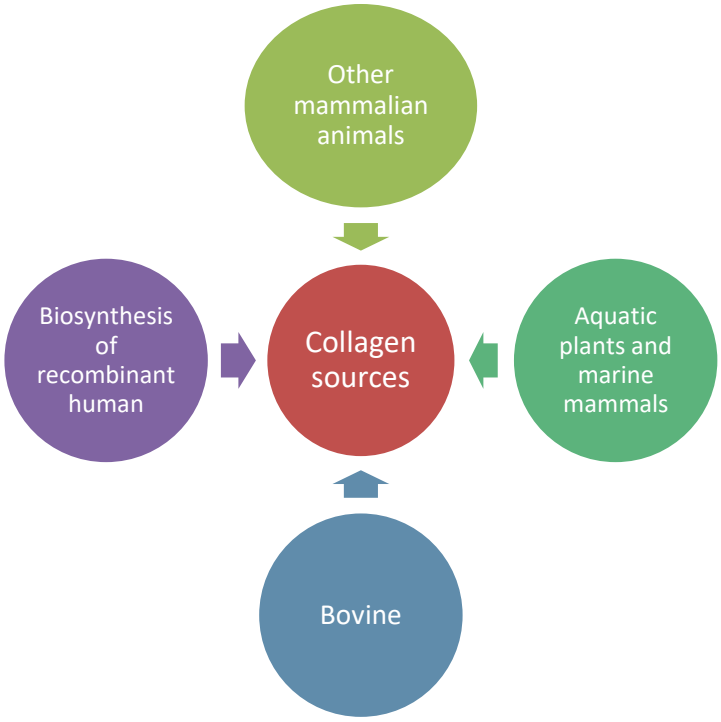


Figure 4 Collagen sources for health technology applications.

Clinical observations have also suggested that nearly 2—4 percent of the population would showcase intolerance and allergies to bovine and porcine derived collagen [63]. Additionally, this percentage does not account for personal or religious beliefs which might affect the patient's decision to accept or decline animal or human-derived collagen products in their treatment plan [63, 64]. Many of the risks associated with animal-derived collagen products could be negated with human-derived collagen but the variation in mechanical and chemical properties between human-derived collagen samples is substantial which hinders their large-scale application [63]. The variation in human-derived collagen is the result of differences in the biophysical profile of placenta caused by genotype of source tissue, environmental setting, age and ethnicity [63]. Recombinant human collagen (rhCOL) biosynthesis was developed to combat the challenges faced with natural human-derived collagen to guarantee consistent and biochemically identical collagen that can be produced at scale [63].

5.1.1 Bovine collagen

Bovine-derived collagen has multiple positive properties like biocompatibility and low immunogenicity which is why it is well-tolerated in vivo and does not evoke immune response in the majority, barring individuals with notable collagen allergies [63]. The type of collagen derived from a bovine depends on where the collagen is extracted from. For example, type I is typically derived from the Achilles tendon and type III is solely acquired from the skin. In some cases, type I collagen can be derived from bone and skin (Figure 5) [63].

Bovine collagen sales make up nearly 35% of all collagen sales, making it the main raw material in collagen-based products [65]. This can be explained with the abundance of raw material as the industrial yield is 8—20%, lower prices (approximately 33 000 USD / metric ton) and long usage history [64, 65]. Despite mammal derived collagen such as bovine collagen being the most widely used collagen, it is not without any safety constraints as there is a significant risk associated with transference of zoonosis diseases like foot and mouth disease (FMD) and several bovine spongiform encephalopathies (BSE) including the prion disease transmissible spongiform encephalopathy (TSE) [64, 65]. Transmissible spongiform encephalopathy (TSE) is a rapidly progressing degenerative brain disorder which causes small holes to form in the brain, leading to a spongy appearance. The disease is caused by an abnormal protein called prion, which is a misfolded form of protein and causes surrounding normal protein to change into similar misfolded forms [64, 66]. These abnormal proteins then stick together and destroy or damage nerve cells [64, 66]. In humans the disease manifests as problems with muscle coordination as well as thinking and usually leads to death within few months or years as there are no cures currently available. With cows, spongiform encephalopathy is more commonly known as Mad Cow Disease [64, 66].

Since bovine collagen can be acquired from Achilles tendon, bone, skin and hide, oftentimes the by-products or sidestreams of other industries like dairy, meat and leather can be used (Figure 5) [67]. The use of by-products from these industries reduces waste however it also ties the collagen production to agriculture which has a substantial GHG emissions footprint at 11% globally [1]. Through research it has been especially noted that cattle contribute the most to greenhouse gas emissions compared to other animals and methane production per cow ranges between 69 to 120 kilograms per year [68]. Taking into consideration as well that in

total there are approximately 1.5 billion cattle globally designated solely for meat production, the total methane released into the atmosphere is at minimum 104 billion kilograms [68].

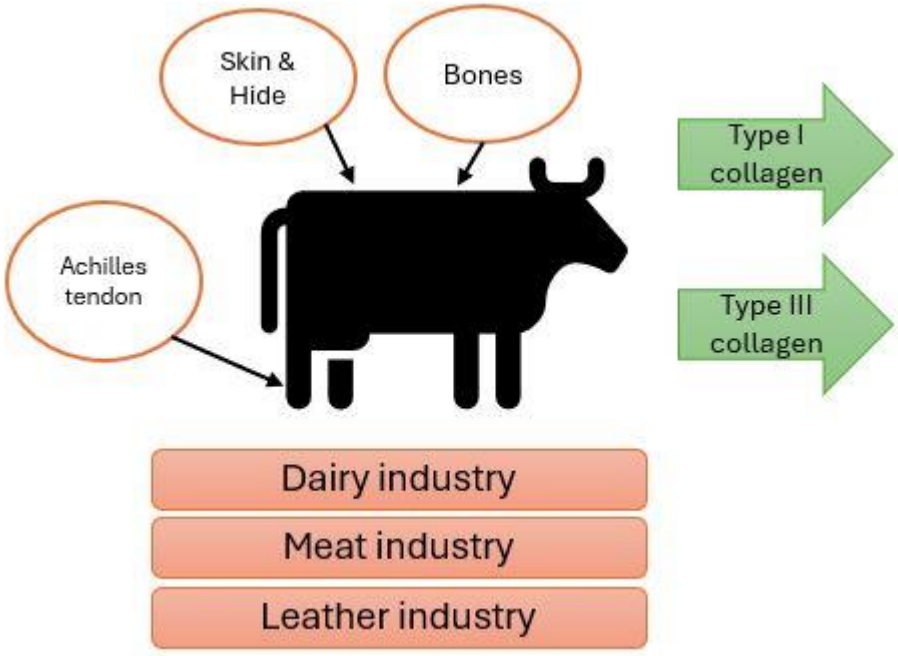


Figure 5 Bovine collagen extraction and industry sources.

Bovine collagen can be sourced practically from anywhere in the world, however specific countries like Brazil, United States of America, Canada, Germany, Spain and China are more common origin regions as they have large agricultural practices [69]. Some ethical concerns have risen with the sourcing of bovine collagen from Brazil as in some cases it has been found that multinational sourcing companies acquire the collagen from farms that contribute actively to the deforestation of tropical forests and to the violence towards the indigenous people of the area [70, 71]. Additionally, since bovine collagen is considered to be a by-product, it is not covered by same traceability and responsible sourcing regulations and standards as some of the other products associated with deforestation [70, 71]. For example, the European Regulation on Deforestation-free Products (EUDR 2023/1115) covers cattle, soy, cocoa and rubber as well as some of their derived products like leather, chocolate and tires, however bovine collagen is not included despite the bovine collagen industry being valued at 4 billion USD a year [70, 71, 72].

5.1.2 Marine collagen

Aquatic-base collagen also known as marine collagen has garnered attention as safer and abundant alternative collagen extraction source as it can be derived from marine organisms such as fish, jellyfish and sponges (Figure 6). [64] When compared to bovine sourced collagen, marine collagen has reduced risks of transmissible diseases, and it is not as limited by religious concerns [64]. In 2024, the total estimated value of international trade of aquatic products (i.e. aquatic animals and algae) was 195 billion USD which came from the acquirement and product of 185.4 million tons of aquatic animals and 37.8 million tons of algae [73]. 89% of all aquatic animal production was used for human consumption and the rest 11 % was applied for non-food uses such as fishmeal or fish oil [73]. The interest in marine collagen is not only limited to health technology applications like in tissue engineering but there are other possible application areas such as food packaging with antibacterial properties [73].

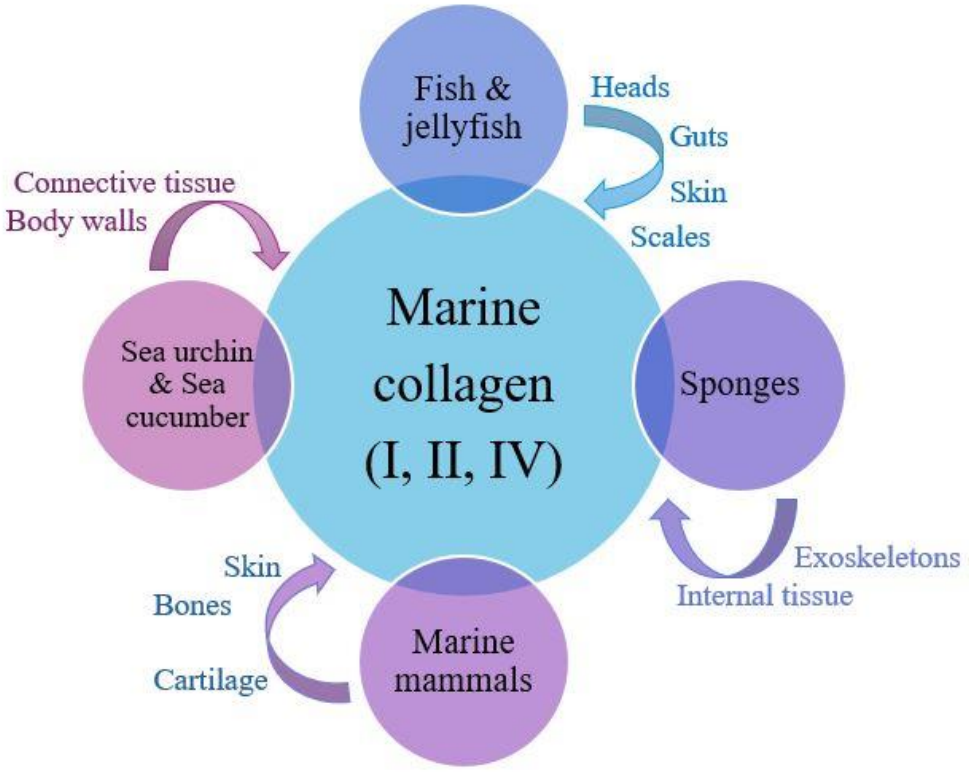


Figure 6 Marine collagen sources and derived collagen types [74].

Marine collagen and bovine-derived collagen share similar collagenous type; however their molecular characteristics differ, and this is especially highlighted due to their differences in amino acid composition [65]. Amino acid composition affects whether the collagen is durable, flexible or if their denaturation requires higher temperatures [65]. The environment

from which marine collagen is sourced from heavily affects the amino acid composition and the properties of the produced collagen [65]. In a study published in 2020, it was noted that the abundance of proline (Pro) and hydroxyproline (Hyp) provide rigidity and stability to the collagen's triple helical structure since both amino acids have a cyclical structure which restrict the rotation of the polypeptide backbone and additionally the hydroxyl group of Hyp creates hydrogen bonds [65, 75, 76]. Moreover, the abundance of Pro in collagen positively affects the thermal stability of the material and the presence of serine (Ser) increases flexibility in fibrous collagen [65, 77]. Case in point for the effect of amino acid content could be made by comparing sea cucumber collagen to mammalian derived collagen [65]. Sea cucumber collagen amino acid composition includes more glycine (Gly) and alanine and less Hyp than mammalian collagen [65]. The lower content of Hyp results in low hydrogen bonds between hydroxy groups which in turn decrease the denaturation temperature of sea cucumber derived collagen compared to mammalian collagen [65]. Other notable positives characteristics of marine collagen are stable regulatory functions, low viscosity, non-toxicity, bio-resorbability and minimal inflammatory response [78].

Despite 89% of all aquatic animal production being used for human consumption, 70—85 % of the total weight of fish catch is either discarded or reduced to by-products. The discarded by-products include heads, fins, scales, skin and guts [64]. Generally marine collagen is represented by two categories: invertebrate and vertebrate collagen. The vertebrate category consists of fish and marine mammals, however, due to several ethical concerns related to marine mammal exploitation, fish derived collagen has become recognized as an excellent collagen source. Additionally, due to fisheries and aquaculture food sector, fish collagen is the most abundant and typical source for marine collagen since inexpensive source materials like fish skin and scales can be used to manufacture high-value collagen [65]. Developing recovery technologies to utilize low value by-products like fish waste to manufacture high-value products, would also solve issues related to pollution of air, soil and water caused by fisheries and fish waste [24]. Most fish collagen utilized in healthcare applications is type I collagen which can be derived from scales and skin. Other types of collagens, like type II and type IV, can be extracted, however they can only be found in fish cartilage and in marine sponges or certain jellyfish respectively [24].

Despite the source materials for fish collagen being relatively inexpensive, the product is quite costly (approximately 45 000 USD / metric ton) due to high cost and complex process of

collagen extraction from fish by-products [64, 78]. Furthermore, the production of fish waste has somewhat decreased in recent years due to changes in fishing regulations to prevent overfishing, which also directly affects the production capacity of fish collagen [78]. The main issues faced with industrial implementation of fish collagen are the low extraction yield, which is species specific and streamlining of the manufacturing process [78].

5.1.3 Recombinant human collagen

Prokaryotic and eukaryotic (i.e. mammalian cells, plants or bacteria) host have been shown to facilitate recombinant human collagen (rhCOL) yet rhCOL's applications are largely limited due to its inability to recreate the full-length molecule with native quantity of post-translational modifications [64]. In prokaryotic systems, the issue with hydroxylation is highlighted as they lack native post-translational mechanisms [64, 79]. While eukaryotic systems include native hydroxylation modules, they are not able to sufficiently hydroxylate collagen molecules, which necessitate the integration of non-native hydroxylases in the ad hoc engineered hosts [64, 79]. rhCOLs have great potential, however the issues faced with hydroxylation makes them expensive and non-biological and therefore, less attractive option for large scale applications [64, 79]. Additionally, rhCOLs are troubled with low yields and the production yield from rhCOLs can range from micrograms to few milligrams per litre of culture [79].

rhCOLs are produced by inserting genetic material into a host organism which then clones the desired protein [33]. The recombinant protein production method is favoured for the production of collagen types II – V as they are harder to source, and the purification process of these collagen types is much more complicated than that of type I collagen [33]. One of the most important benefits of rhCOLs is the safety of the produced collagen as the risks for zoonotic disease contamination and immunogenic reactions are minimized due to highly controlled manufacturing environment and no animal sourced tissues are used [80].

5.2 Chitosan

Chitin, from which chitosan is derived from, can be found from various sources such as exoskeletons of crustaceans, molluscs, fungi and insects [45]. Chitosan can be manufactured either through chemical or biological processes (Figure 7), however chemical manufacturing is the more industrially favoured method due efficiency, higher yield and control [47, 81]. In chemical processing, the shell waste from crustaceans (e.g. crab, crawfish and shrimp) is first rinsed and crushed, after which they are subjected to sodium hydroxide to deproteinize the shells [47]. The deproteinized shells are then demineralized through a hydrochloric acid treatment after which the shells go through the decolouration and bleaching phase that results in raw chitin [47]. In the last processing phase, raw chitin is deacetylated in alkaline conditions and the resulting chitosan from deacetylation is dried [47]. Manufacturing chitosan through chemical processes results in chemical waste as well as by-products, mainly proteins and minerals such as calcium carbonate and calcium phosphate [47].

The biological manufacturing of chitosan includes more processes steps than the chemical processing, making the manufacturing slower as well as requiring bioreactors and enzymes, which makes biological processing also the more expensive option out of the two [47, 81]. In biological manufacturing, crustacean shell waste can be either fermented with lactic acid and proteolytic bacterium or hydrolysed with protease (Figure 7) [47]. Both manufacturing options require centrifugation at a certain point to separate the solid phase, containing chitin, and liquid fraction from one another. As with chemical processing, the liquid fraction comprises of proteins, mainly pigments and peptides [47].

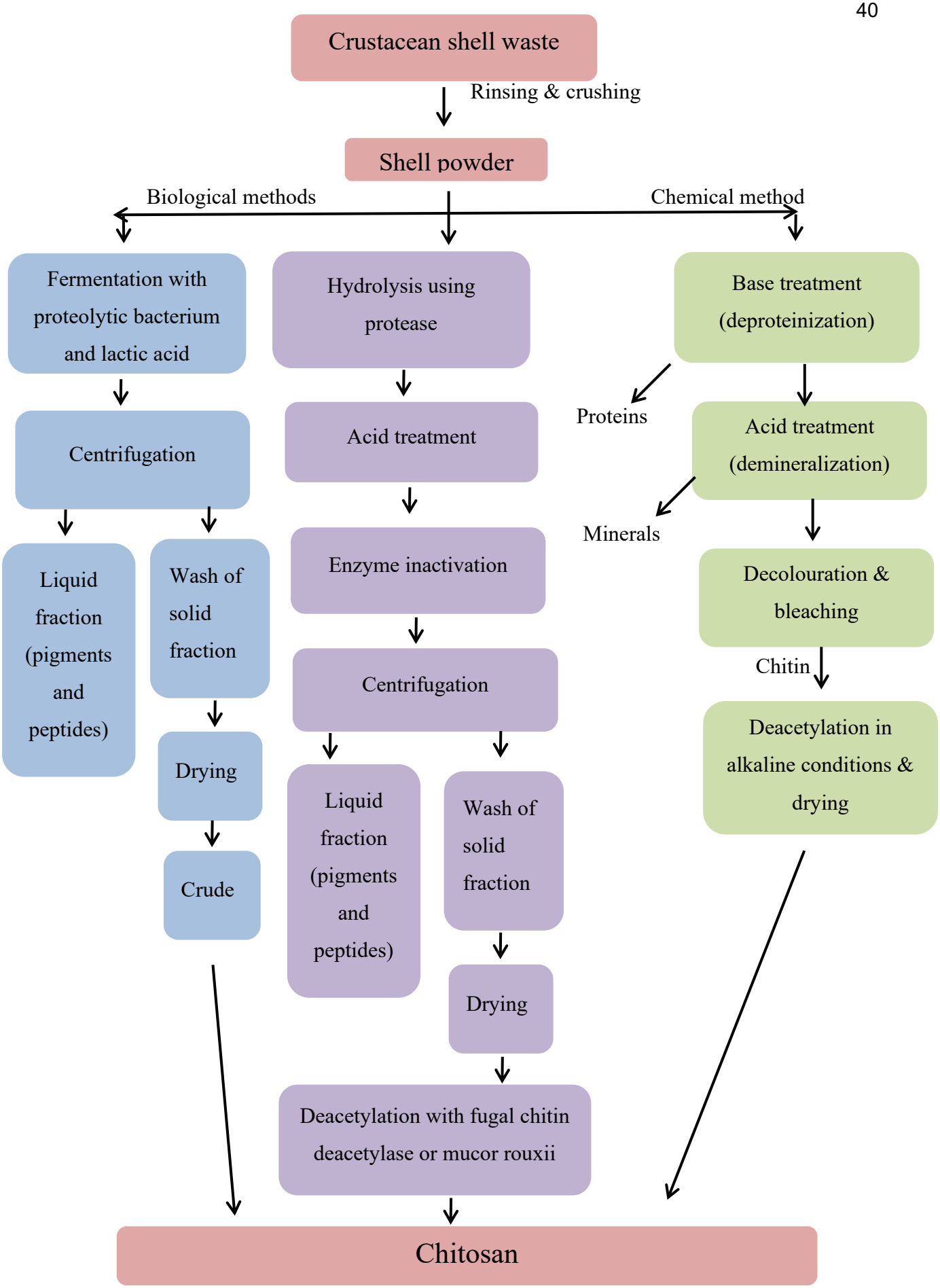


Figure 7 Chitosan manufacturing methods [47].

5.2.1 Chitosan derived from invertebrates

The most common invertebrate sources for chitosan are the exoskeletons of crustaceans such as lobster, shrimp, barnacle or crayfish as well as molluscs like octopus, squid, oysters and clams [45]. The amount for chitosan precursor chitin varies between invertebrates and shrimp cuticles exhibit the highest amount of chitin with 30—40% of the organism consisting of chitin. Other invertebrate sources possess lower amounts of chitin, typically crustacean exoskeletons with 20—30% and crab cuticles 15—30% [45]. Majority of the currently utilized chitosan can be sourced to crustacean sources due to the abundance of available exoskeletons derived from food processing industry's waste [45]. More specifically, 80% of the chitosan products available in the economic market can be traced back to shrimp shells [45].

Applying invertebrate waste for manufacturing industrial, food grade or medical grade chitosan decreases the amount of organic waste to be disposed of and helps in sustaining the water quality [82]. Oftentimes the organic waste generated from shellfish processing is disposed of into coastal waters located near the processing facilities and the amount of waste discharged into the water surpasses the assimilative capacity of the body of water leading to eutrophication [82]. The presence of excess waste in water leads to reduced amount of dissolved oxygen available, increasing the presence of organic matter and critical nutrients, namely potassium, nitrogen and phosphorus [82]. The increased concentrations of these nutrients promote growth in fish population short-term, however it also promotes the growth of types of algal blooms which produce toxins [82]. The lack of dissolved oxygen and algal blooms in combination result in mass mortality of species present in the water [82]. Chitosan manufacturing not only creates a high value material for medical applications and wastewater treatment but also greatly reduces the amount of waste discarded to the environment [82].

Chitosan has multiple useful properties such as antioxidant activity, blood-compatibility and anti-bacterial, however the material applications are restricted by its limited solubility and weak mechanical properties [47]. Both limitations can be reduced through material alternation and making, for example, the materials chitosan-based instead of only pure chitosan. Often chitosan is utilized in wound dressing to enhance the wound healing process and discourage any infections, however some level of cytotoxicity is generated by the process and further

research is necessary to address the concerns to permit widescale application of chitosan and its composites in therapeutic uses [47].

To produce 1 kilogram of chitosan, 1.2 kilograms of chitin is needed [81]. Medical grade chitosan derived from invertebrates demands extensive purification processing which is also reflected in the pricing as the material can be priced at 58 000 USD per metric ton [81]. Compared to other materials, like bovine- or marine-derived collagen, chitosan is more expensive which makes it less attractive to health technology manufacturers. Additionally, deriving chitosan from invertebrates ties the chitosan manufacturing to the fishing industry and its possible ethical issues such as overfishing, environmental pollution and forced labour. Chitosan manufacturing should utilize waste generated by the fishing industry but it's important that chitosan manufacturing itself doesn't promote further fishing nor ecosystem damage.

5.2.2 Insect derived chitosan

Insect derived chitosan is one of the promising alternatives for crustaceans derived chitosan as insect farming benefits from better efficiency in feed conversion, functions with less natural resources such as water and land area and produces less GHGs [83]. In addition to these benefits, the insects contribute to sustainability by reducing waste and promoting recycling through the conversion of organic waste into protein sources [83]. Insect farming is an attractive option for manufacturers since it's scalable and the chitosan extraction process produces high value biomass which can be sold to pet food or biological fuel manufacturers [83, 84]. As with other chitosan types, insect derived chitosan has many positive attributes such as anti-coagulant, anti-inflammatory and antibacterial [85]. Compared to crustacean sourced chitosan, insect derived chitosan, especially from black soldier fly, exhibits superior antimicrobial and antifungal activity against bacteria such as Gram-negative *Escherichia coli* and Gram-positive *Micrococcus flavus* as well as fungus *Fusarium oxysporum* [83, 84]. Another notable benefit of chitosan sourced from insects is the lowered risk of allergic reactions [83].

The yield and concentration of insect derived chitosan is heavily dependent on the environment and rearing conditions, such as the variety and quality of the nutrition feed. This allows for the finetuning of chitosan properties and facilitates application specific material

engineering [83]. The biomass of insects consists of 5—30% of chitin and their exoskeletons usually contain more than 30% chitin by mass which places their chitin mass as equal or more than what crustacean exoskeletons can offer [83]. The insects utilized in chitosan manufacturing include black soldier fly (*Hermetia illucens*), house flies (*Musca domestica*), yellow mealworms (*Tenebrio molitor*), superworms (*Zophobas morio*) and field crickets (*Gryllus bimaculatus*) [84].

5.2.3 Fungi derived chitosan

Fungi are the second most utilized source for chitosan, and their cell walls contain 1—15% chitin [83]. Not all fungi contain chitin but a wide variety including, Basidiomycota, Ascomycota, and Zygomycota do contain chitin [84]. Fungi derived chitosan can be considered more environmentally sustainable option to crustacean derived chitosan, however the fungal manufacturing method is not without its risks [86]. The risks associated with fungal manufacturing of chitosan are highly species specific and can range from minor to severe [86]. One of the most significant fungal chitosan sources is *Colletotrichum lindemuthianum*, yet the fungi is the causative factor for plant disease anthracnose, which causes leaf spots and early leaf dropping [86]. Among Zygomycetes fungi class, *Absidia* and *Rhizopus* can cause severe damage with pathogens if they are utilized incorrectly [86]. Among *Absidia* species, some can trigger mucormycosis, a severe fungal infection with high fatality rate, for individuals with compromised immune systems. Other Zygomycetes, such as *Rhizopus oryzae* may function as opportunistic pathogens and result in pulmonary mucormycosis [86]. Due to the possible presence of pathogenic strains within the fungi, it's crucial that specific quality measurements are applied to prevent the incidental spreading of pathogens [86].

Fungi derived chitosan benefits from medium to low molecular weight which makes it more soluble than crustacean derived chitosan [86]. Furthermore, chitosan originating from fungi doesn't contain allergenic proteins, such as tropomyosin which makes the material more attractive for medical applications [86]. Other notable benefits of fungal based chitosan include being free of heavy metals, like nickel and copper, not being limited by seasonal variation, low polydispersity index and biocompatibility [87]. The material is valued at between 50—5000 USD per kg based on market continent and country, with lower prices being based in China and Europe [87].

5.3 Alginate

Brown algae is a great source for a variety of valuable molecules, including polymers, phenolic compounds, proteins and carotenoids [88]. Key polymers, such as alginate, laminarin and fucoidan, can be derived from brown algae cell walls [88]. The main polymer derived from brown algae is alginate since it accounts for nearly 40 percent of the dry weight of brown algae [88]. In commercial setting, alginate is primarily obtained from brown algae in the form of soluble sodium alginate, and it is the main form of alginate used in heath technology applications such as health monitoring sensors [88]. In 2014, the annual production of alginate was almost 23 000 tons, while in 2021 the production had increased to over 300 000 tons [54, 88, 89]. The current process for extracting alginate relies heavily on the use considerable volumes of solvents and reagents which makes the extraction process lengthy and to a degree unsustainable [88]. The extraction processing usually is executed in 6 phases: pre-treatment, acid treatment, alkaline extraction, precipitation, bleaching and lastly drying [88].

Natural alginate can be found in an insoluble mixed salt of alginic acid and numerous cations, primarily with calcium, magnesium, sodium and potassium [57, 88]. Alginate can be sourced from Phaeophyceae class of algae and more specifically from orders of Fucales and Laminariales [54, 88]. *Macrocystis pyrifera* and *Ascophyllum nodosum* are the primary species utilized for the manufacturing of industrial alginate, however there are other algae species such as *Ecklonia maxima*, *genus Laminaria* and *Sargassum* which can be used in alginate fabrication [54, 88]. The extraction and decontamination of alginate is conventionally executed through ion exchange methods due to alginate manifesting as insoluble salts in algal cell walls [54]. Since traditionally the fabrication of alginate has relied heavily on toxic chemical solvents, new novel ways have been developed to minimize or terminate the use of these solvents. In addition, both energy and time efficiency have been an area of focus to achieve better quality alginate as well as to enhance the yield of fabrication processes [88]. The main ways to enhance the manufacturing performance is to include pre-treatment and cell disruption techniques [88].

The biocompatibility of alginate has been well established for *in vivo* applications in various forms such as ocular, topical, local and oral [54, 90]. Other notable safety enhancing properties for alginate are its non-immunogenicity, biodegradability and non-toxicity [54, 90].

Alginate hydrogels are not degradable in mammalian digestive tract and as such the biodegradability of alginate is based on the gradual elution of multivalent ions, which ultimately results in their dissolution [90]. Since alginate is manufactured from seaweed, it is not hindered by the same ethical and religious beliefs as, for example bovine derived collagen. Additionally, allergic reactions associated with alginate as quite rare, despite its widespread usage [91, 92].

"Blue bioeconomy" is one of the initiatives in the European Green Deal and the purpose of it, is to decrease the pressure placed on the EU's land resources as well as to address the needs set for inhibiting the progress of climate change [93]. The European Union's bioeconomy strategy creates means to address the needs for sustainable growth and material sourcing as well as generating innovations, services and work opportunities [93, 94]. As mentioned previously, *Ascophyllum nodosum* is one of the primary macroalgae species from which industrial alginate is derived from and the algae is abundantly available along the European shores, from Iceland and northern Norway, all the way until northern Portugal [54, 88, 95]. The collection of macroalgae is largely dependent on wild stocks as only 32% of macroalgae production is based on macroalgae aquaculture [94]. Countries such as France, Ireland and Spain represent the largest macroalgae producers in Europe and in parts of the coastal area there are longstanding cultural traditions for the gathering of seaweeds used for fertilizer, cattle feed or food purposes [94]. Creating economic opportunities with marine biomass within Europe can help with material transparency and implementing environmentally as well as socially sustainable harvesting practices [94].

6 Challenges and future trends

Recent advances with Internet of Things (IoT) and artificial intelligence have enabled the further development of flexible and wearable sensors fabricated from sustainable materials like collagen and other natural organic polymers [40]. Flexible and wearable sensors have demonstrated great potential in diverse applications for detection and healthcare where sensitivity and reactivity are of utmost importance [40]. In addition to the "traditional" wearable sensors and health devices, smart fabrics which have inlayed sensors, such as sweat or monition sensors, have gained a growing interest as they could be applied to healthcare for disease diagnosis and real-time monitoring of patient's recovery at the injury or operating site [96, 97]. Furthermore, smart fabrics would be advantageous in the sports sector for performance measurement, injury prevention or monitoring [96].

In the case of collagen, the optimization of smart wound dressings and the embedded sensor functionality is a key focus for the future as they could prove to be pivotal in future healthcare processes for diagnosis and disease management [38]. To achieve the wide scale application of smart wound dressings, many performance properties such as long-term stability, sensitivity and accuracy need to be improved and further researched [38]. Other major hinderances are the operating limitations as extreme temperature environments present a major obstacle for the sensors embedded in the dressings [38]. The denaturation temperature, lack of mechanical strength and swelling in water/vacuum have been some of the obstacles against the implementation of collagen in device manufacturing, however in recent years more effort has been put into developing fabrication techniques which combat these shortcomings and allow the manufacturing of more permanent electronics [28, 39]. In terms of collagen sourcing and extraction, bovine collagen has traditionally dominated the commercial market, however marine sourced collagen has gained more interest in recent years as has less risks associated in regard to diseases and smaller GHGs footprint [64, 65, 68]. Marine based collagen offers many opportunities in biomedical field, nonetheless the industrial applications are hindered by low extraction yield meaning that future innovation is needed to streamline and scaling up the manufacturing processes of marine-derived collagen [78].

The implementation of chitosan based hydrogels in sensor applications is strongly hindered by its limited solubility and mechanical properties such as weak stability in harsh

environmental conditions, the evaporation of water in dry and high temperature conditions as well as the moisture condensation in low-temperature conditions [47, 51]. Another noteworthy consideration for chitosan utilization is the operating range of the sensors as the response baseline will be affected by chitosan hydrogel's degree of deformation [51]. When chitosan-based hydrogels are used for sensor applications, electrode corrosion is one of the most crucial things to consider due to the accumulation of reaction products on the sensor surface when voltage is applied for extended periods of time [51]. The accumulation of reaction products strongly influences the service life and performance of the sensor [51]. The use of chitosan to wearable sensor applications is encouraged due to the materials good biocompatibility, however the material is hindered by poor air permeability, which can result in skin inflammation due to skin being unable to breathe after long-term contact with chitosan based materials [51]. In the last few years, a great deal of research has been done to discover chitosan's potential for e-skin, wearable devices as well as medical electronics applications and for future it seems that the aim is to establish manufacturing techniques which can minimize the negative properties of the material and to enable large scale use of chitosan in long-term commercial applications [51]. QCM, resistance and colorimetric-based chitosan hydrogel sensors represent the majority of researched humidity sensors for health monitoring, however recently it has been noted that chitosan also exhibits advantageous capacitive properties and as such capacitive-based humidity sensors are an area of future interest [53]. In regard to chitosan sourcing, insect and fungi derived chitosan is predicted to gain more interest and foothold in the commercial innovation settings as they offer a more sustainable and possibly economical alternative to crustacean derived chitosan [83].

Alginate had exhibited long-term stability as well as biocompatibility in health monitoring applications such as real-time monitoring of biomarker levels [58]. Nonetheless, real-life applications of alginate hydrogels are limited by reproducibility and fast gelation time which cause greatly heterogeneous structures [58]. It has been determined that alginate hydrogels solely on their own are not adequate to comply with the standards set for materials in biomedical applications [58]. Thus, further research needs to be undertaken to discover which additional materials should be added to alginate hydrogels to improve their performance [58].

7 Conclusions

Sustainability has a long history and throughout its course the term has had many definitions, however the most prevalent and common definition even until this date can be traced to the United Nations Brundtland Commission report of 1987 (“Our Common Future). The United Nations Framework convention on climate change (Paris Agreement 2015) provided a further consensus on which chemical compounds are classified as greenhouse gases (GHGs) and how sustainability needs to be implemented with the three pillars (Environmental, Social and Governance) taken into consideration. Healthcare services account for 4.4% of net global GHG emissions, however in highly industrialised nations the proportional percentage can be up to 10% as there is a strong correlation between a country’s GDP, healthcare spending and healthcare sector’s climate footprint.

In addition to the United Nation agreements, standards and regulations are needed together as standards provide mutually recognized good practices and regulation provides the means to enforce the mutually agreed environmental targets and practices. While standards are voluntary, they often make compliance with regulation more efficient. Examples of widely applied environmental and sustainability standards are Greenhouse Gas Protocol (2022) as well as ISO standards 14001 for EMS and 14040/14044 for LCA. In the healthcare sector, the majority of the generated emission can be traced to scope 3 indirect emissions via manufacturing, transportation and distribution of goods and services.

Natural organic polymers such as collagen, chitosan and alginate are viable material options for health monitor applications as they are highly customizable and biocompatible, they can be derived from various renewable sources and depending on the material source they can also be quite cost efficient. Alginate represents a significant opportunity to decrease the pressure on land resources as well as create new economic possibilities for previously underutilized resources. While bovine collagen has been the most widely applied collagen for health technology innovations in the past, marine-derived collagen exhibits excellent potential in terms of function and sustainability. Marine collagen can be derived for example from fish, sponges or sea cucumber and it is in many cases considered to be safer than bovine-derived collagen as there is a lowered risk of transmissible diseases. Insect and fungi derived chitosan exhibit great prospects in health monitoring applications as they have lowered risks of allergic reactions when compared to the traditional crustacean derived chitosan.

In the past few years there has been a significant push to conduct research on sustainable and renewable materials such as collagen, chitosan and alginate for the health technology industry. There have been various research articles produced on the potential of these materials in smart healthcare applications such as sensors meant for pharmaceutical and humidity detection as well as wound dressing with sensors imbedded in them. While collagen, chitosan and alginate do showcase potential in sensor applications, at the moment their clinical and commercial applications are limited by complex manufacturing processes, insufficient mechanical properties and performance issues in extreme temperatures. Currently the application of these materials in sensor manufacturing is limited to laboratory scale, however further research is being conducted to enable commercialization and large-scale application.

8 References

[1] Center for climate and energy solutions (C2ES), “Global Emissions,” 2022.

[2] United Nations, “Sustainability”.

[3] United States Environmental Protection Agency (EPA), “Overview of Greenhouse Gases,” 2025.

[4] NH Global: Scott Slotterback, Richard Boyd, Ben Ashby, Kristian Steele, “Health care climate footprint report,” 2021.

[5] K. Usher, J. Williams and D. Jackson, “The potential of virtual healthcare technologies to reduce healthcare services' carbon footprint.,” 2024.

[6] M. Crippa, D. Guizzardi, F. Pagani, M. Banja, M. Muntean, E. Schaaf, F. Monforti-Ferrario, W. Becker, R. Quadrelli, A. Risquez Martin, P. Taghavi-Moharamli, J. Köykkä, G. Grassi, S. Rossi, J. Melo, D. Oom, A. Branco, J. San-Miguel, G. Manca, E. Pisoni, E. Vignati and F. Pekar, “GHG emissions of all world countries: 2024 Report,” The European Commission, Luxembourg, 2024.

[7] European Commission, “About F-gases,” 2023.

[8] United States Environmental Protection Agency (EPA), “Scope 1 and Scope 2 Inventory Guidance,” 2024.

[9] United States Environmental Protection Agency (EPA), “Greenhouse Gas Inventory Guidance : Direct Emissions from Stationary Combustion Sources,” 2023.

[10] Greenhouse Gas Protocol, “Scope 2 Guidance,” 2022.

[11] United States Environmental Protection Agency (EPA), “Scope 3 Inventory Guidance,” 2024.

[12] Greenhouse Gas Protocol, “Corporate Value Chain (Scope 3) Accounting and Reporting Standard,” 2011.

[13] NH Global: Scott Slotterback, Richard Boyd, Ben Ashby, Kristian Steele, “Health care’s climate footprint report Appendix C: Health care emissions national snapshots,” 2021.

[14] Valtioneuvosto: Pulkki, Jutta; Wulff, Pia; Iivonen, Saija; Alanko, Leena; Alhola, Katriina; Frilander, Oona; Hiilamo, Heikki; Meriläinen , Päivi; Nissinen, Ari; Savolainen, Hannu; Suomalainen, Emilia; Setälä, Leena;, “Ekologisesti kestävä,” Valtioneuvoston kanslia, Helsinki, 2023.

[15] American Society for Quality (ASQ), “What Is ISO 14001:2015 – Environmental Management Systems?,” 2024.

[16] International Organization for Standardization (ISO), “What we do?,” 2025.

[17] American Society for Quality (ASQ), “What Are Environmental Management Systems (EMS)?,” 2025.

[18] Internation Organization for Standardization (ISO), “ISO 14001:2015 Environmental management systems — Requirements with guidance for use,” 2015.

[19] DQS Holding GmbH, “ISO 14040 and 14044 - Review of Life Cycle Assessments,” 2025.

[20] International Organization of Standardization (ISO), “ISO 14044:2006(en),” 2006.

[21] European Commission, “Overview on health technology assessment”.

[22] L. Rodríguez-Jiménez, m. Romero-Martín, T. Spruell, Z. Steley and J. Gómez-Salgado, “The carbon footprint of healthcare settings: A systematic review,” Journal of Advanced Nursing, 2023.

[23] European Commission, “Implementation of the Regulation on health technology assessment,” 2022.

[24] The European Parliament, “REGULATION (EU) 2021/2282 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL,” 2021.

[25] European Commission, “Life Cycle Assessment & the EF methods,” 2024.

[26] E. S. Hosseini, S. Dervin and R. Dahiya, “Biodegradable Materials for Sustainable Health Monitoring Devices,” ACS Applied Bio Materials, 2020.

[27] Z. T. P. M. Huang NF, “Biomedical Applications of collagen,” Basel, 2023.

[28] M. M. Marin, R. Ianchis, R. L. Alexa, I. C. Gifu, M. G. A. Kaya, D. I. Savu, R. C. Popescu, E. Alexandrescy, C. M. Ninciuleanu, S. Preda, M. Ignat, R. Contantinescu and H. Iovu, “Development of New Collagen/Clay Composite Biomaterials.,” International journal of molecular sciences, 2021.

[29] M. D. a. R. T. R. Shoulders, “Collagen structure and stability,” Annual review of biochemistry, 2009.

[30] T. Miklovis and V. C. Sieg, “Ehlers-Danlos Syndrome,” 2023.

[31] M. Abedi, M. Shafiee, F. Afshari, H. Mohammadi and Y. Ghasemi, “Collagen-Based Medical Devices for Regenerative Medicine and Tissue Engineering,” Applied biochemistry and biotechnology, 2023.

[32] Y. Zhang, Y. Wang, Y. Li, Y. Yang, M. Jun, X. Lin, Z. Zhuang, K. Guo, T. Zhang and W. Tan, “Application of Collagen-Based Hydrogel in Skin Wound Healing,” Gels, Basel.

[33] Q. Xu, J. E. Torres, M. Hakim, P. M. Babiak, P. Pal, C. M. Battistoni, M. Nguyen, A. Panitch, L. Solorio and J. C. Liu, “Collagen- and hyaluronic acid-based hydrogels and their biomedical applications,” Materials science & engineering. R, Reports : a review journal, 2021.

[34] E. Entekhabi, M. H. Nazarpak, M. Shafieian, H. Mohammadi, M. Firouzi and Z. Hassannejad, "Fabrication and in vitro evaluation of 3D composite scaffold based on collagen/hyaluronic acid sponge and electrospun polycaprolactone nanofibers for peripheral nerve regeneration," Journal of Biomedical Materials Research, 2020.

[35] MatriDerm, "What is MatriDerm®?," 2025.

[36] Intergra, "Integra® Wound Matrix," 2025.

[37] 3M, "3M™ Fibracol™ Plus Collagen Wound Dressing with Alginate, 2982, 10.2 cm x 11.1 cm, 12/Ct," 2025.

[38] Q. Pang, F. Yang, Z. Jiang, K. Wu, R. Hou and Y. Zhu, "Smart wound dressing for advanced wound management: Real-time monitoring and on-demand treatment," Materials & Design, 2023.

[39] S. Moreno, J. Keshtkar, R. A. Rodriguez-Davila, A. Bazaid, H. Ibrahim, B. J. Rodriguez, M. A. Quevedo-Lopez and M. Minary-Jolandan, "Bioelectronics on Mammalian Collagen," Advanced Electronic Materials, 2020.

[40] X. Zhang, J. Liu, L. Li, X. Zheng, K. Tang and Y. Pei, "Collagen-Based Flexible Electronic Devices for Electrochemical Energy Storage and Sensing," Macromolecular Rapid Communications, 2023.

[41] N. Li, S. Kang, Z. Liu, S. Wai, Z. Cheng, Y. Dai, A. Solanki, S. Li, Y. Li, J. Strzalka, M. J. White, Y.-H. Kim, B. Tian, J. A. Hubbell and S. Wang, "Immune-compatible designs of semiconducting polymers for bioelectronics with suppressed foreign-body response," Nature Materials, 2025.

[42] B. Song, X. Fan, q. Shen and H. Gu, "Ultra-stable and self-healing coordinated collagen-based multifunctional double-network organohydrogel e-skin for multimodal sensing monitoring of strain-resistance, bioelectrode, and self-powered triboelectric nanogenerator," Chemical Engineering Journal, 2023.

[43] A. Bougea, "Application of Wearable Sensors in Parkinson's Disease: State of the Art," Journal of Sensor and Actuator Networks (JSAN), 2025.

[44] P. Baharlouei and A. Rahman, "Chitin and Chitosan: Prospective Biomedical Applications in Drug Delivery, Cancer Treatment, and Wound Healing," Marine drugs, 2022.

[45] A. Pellis, G. M. Guebitz and G. S. Nyanhongo, "Chitosan: Sources, Processing and Modification Techniques," Gels, Basel, 2022.

[46] S. Krishnan, K. Chakraborty and S. Dhara, "Biomedical potential of β-chitosan from cuttlebone of cephalopods," Carbohydrate Poloymers, 2021.

[47] H. Yadav, R. Malviya and N. Kaushik, “Chitosan in biomedicine: A comprehensive review of recent development,” Carbohydrate Polymer Technologies and Applications, 2024.

[48] I. Aranaz, A. Alcántara, M. C. Civera, C. Aria, B. Elorza, A. H. Cabellero and N. Acosta, “Chitosan: An Overview of Its Properties and Applications,” Polymers, 2021.

[49] A. V. Bounegru and I. Bounegru, “Chitosan-Based Electrochemical Sensors for Pharmaceuticals and Clinical Applications,” Polymers, 2023.

[50] R. Jin, J. Xu, L. Duan and G. Gao, “Chitosan-driven skin-attachable hydrogel sensors toward human motion and physiological signal monitoring,” Carbohydrate Polymers, 2021.

[51] S. Wu, C. Xu, Y. Zhao, W. Shi, H. Li, J. Cai, F. Ding and P. Qu, “Recent Advances in Chitosan-Based Hydrogels for Flexible Wearable Sensors,” Chemosensors, 2023.

[52] P. Kumari, A. Kumar, A. Yadav, G. Gupta, G. Gupta, D. D. Shivagan and K. Bapna, “Chitosan-Based Highly Sensitive Viable Humidity Sensor for Human Health Monitoring,” ACS Omega, 2023.

[53] A. He, h. yan, G. Zheng, R. Zhou, Y. li, Z. Ye and Z. Chentao, “A high-sensitive capacitive humidity sensor based on chitosan-sodium chloride composite material,” Colloids and Surface A: Physicochemical and Engineering Aspects, 2024.

[54] R. Abka-khajouei, L. Tounsi, N. Shahabi, A. K. Patel, S. Abdelkafi and P. Michaud, “Structures, Properties and Applications of Alginates,” Marine Drugs, 2022.

[55] K. Y. Lee and D. J. Mooney, “Alginate: properties and biomedical applications,” Prog Polym Sci, 2012.

[56] S. L. Tomic, M. M. Radic, j. S. Vukovic, V. V. Filipovic, J. Nikodinovic-Runic and M. Vukomanovic, “Alginate-Based Hydrogels and Scaffolds for Biomedical Applications,” Mar. Drugs, 2023.

[57] M. Rahman, A. Shahid, T. Hossain, S. Sheikh, S. Rahman, N. Uddin, A. Rahim, R. A. Khan and I. Hossain, “Sources, extractions, and applications of alginate: a review,” Discover Applied Sciences, 2024.

[58] D. M. Roquero and E. Katz, ““Smart” alginate hydrogels in biosensing, bioactuation and biocomputing: State-of-the-art and perspectives,” Sensors and Actuators Reports, 2022.

[59] S. Garcia-Rey, E. Ojeda, U. B. Gunatilake, L. Basabe-Desmonts and F. Benito-Lopez, “Alginate Bead Biosystem for the Determination of Lactate in Sweat Using Image Analysis,” Biosensors, 2021.

[60] B. Ibarlucea, A. P. Roig, D. Belyaev, L. Baraban and G. Cuniberti, “Electrochemical detection of ascorbic acid in artificial sweat using a flexible alginate/CuO-modified electrode,” Microchimica Acta, 2020.

[61] M. Debije and A. H. Schenning, “Stimuli-Responsive Liquid Crystalline Materials,” Reference Module in Materials Science and Materials Engineering, 2016.

[62] Z. Wang, X. Han, G. Sun, M. Yu, J. Qin, Y. Zhang and D. Ding, “Advances in cancer diagnosis and therapy by alginate-based multifunctional hydrogels: A review,” International Journal of Biological Macromolecules, 2024.

[63] . E. Davison-Kotler, W. Marshall and E. García-Gareta, “Sources of Collagen for Biomaterials in Skin Wound Healing,” Bioengineering, 2019.

[64] L. Salvatore, N. Gallo, M. L. Natali, L. Campa, P. Lunetti, M. Madaghiele, F. S. Blasi, A. Corallo, L. Capobianco and A. Sannino, “Marine collagen and its derivatives: Versatile and sustainable bio-resources for healthcare,” Materials Science and Engineering: C, 2020.

[65] J. A. Panggabean, S. P. Adiguna, M. HArdhiyuna, S. I. Rahmawati, N. H. Sadi, G. P. Yoga, E. Nafisyah, A. Bayu and M. Y. Putra, “Cutting Edge Aquatic-Based Collagens in Tissue Engineering,” Marine drugs, 2023.

[66] National Institute of Neurological Disorders and Stroke (USA), “Transmissible Spongiform Encephalopathies”.

[67] T. P. Basso, L. c. Basso and T. O. Basso, biotechnological applications of biomass, 2021, pp. 203-205.

[68] United States Environmental Protection Agency (EPA), “Agriculture and Aquaculture: Food for Thought,” 202.

[69] U.S Food & Drug Administration, “Collagen and Gelatin Export Lists,” 2022.

[70] E. Mendonça, F. Zuker and A. Wasley, “Collagen Craze Drives Deforestation and Rights Abuses,” 2023.

[71] E. Mendonça, F. Zuker, G. Murray and A. Wasley, “‘No Excuse’ for Collagen Brands Sourcing From Deforested Land,” 2023.

[72] The European Union, “Regulation on Deforestation-free Products,” 2024.

[73] Foof and Agriculture Organization of the United Nations, “The State of World Fisheries and Aquaculture 2024,” FAO, Rome, 2024.

[74] S. Farooq, M. I. Ahmad, S. Zheng, U. Ali, Y. Li, C. Shixiu and H. Zhang, “A review on marine collagen: sources, extraction methods, colloids properties, and food applications,” Collagen and Leather, 2024.

[75] T. V. Burjanadze, “New analysis of the phylogenetic change of collagen thermostability,” Biopolymers, 2008.

[76] M. D. Shoulders, I. A. Guzei and T. R. Raines, “4-Chloroprolines: Synthesis, conformational analysis, and effect on the collagen triple helix,” Biopolymers, 2007.

[77] L.-L. Yang, S.-K. Tang, Y. Huang and X.-Y. Zhi, “Low Temperature Adaptation Is Not the Opposite Process,” Genome Biology and Evolution, 2015.

[78] Z. Rajabimashhadi, N. Gallo, L. Salvatore and F. Lionetto, “Collagen Derived from Fish Industry Waste: Progresses and Challenges,” Sustainable biopolymer-based composites: processing, characterization, and application, 2023.

[79] T. Wang, J. Lew, J. Prempkumar, C. L. Poh and M. W. Naing, “Production of recombinant collagen: state of the art and challenges,” Engineering Biology, 2017.

[80] L. Cao, Z. Zhang, D. Yuan, M. Yu and J. Min, “Tissue engineering applications of recombinant human collagen: a review of recent progress,” Front Bioeng Biotechnol, 2024.

[81] A. Riofrio, T. Alcivar and H. Baykara, “Environmental and Economic Viability of Chitosan Production in Guayas-Ecuador: A Robust Investment and Life Cycle Analysis,” ACS Omega, 2021.

[82] I. Junceda-Mena, E. García-Junceda and J. Revuelta, “From the problem to the solution: Chitosan valorization cycle,” Carbohydrate Polymers, 2023.

[83] H. L. Schäger, L. Gandras, L. Scheider, M. Witthohn, K. Troidl, K. Muffler and C. K. Weiss, “Analysis, Properties, and Applications of Insect-Derived Chitosan: A Sustainable Path to Functional Polysaccharide Materials,” Gels, 2025.

[84] K. u. Rehman, C. Hollah, K. Wiesotzki, V. Heinz, K. Aganovic, R. u. Rehman, J.-I. petrusan, L. Zheng, J. Zhang, S. Sohail, M. K. Mansoor, C. I. Rumbos, C. Athanassiou and M. Cai, “Insect-Derived Chitin and Chitosan: A Still Unexploited Resource for the Edible Insect Sector,” Sustainability, 2023.

[85] M. Martingo, S. Baptista-Silva, R. Mesquita, J. P. Ferreira, S. Borges and M. Pintado, “Exploring the potential of mealworm chitosan for hemodialysis applications,” Sustainable Chemistry and Pahrmacy, 2025.

[86] S. Crognale, C. Russo, M. Petruccioli and A. D'Annibale, “Chitosan Production by Fungi: Current State of Knowledge, Future Opportunities and Constraints,” Fermentation, 2022.

[87] T. Huq, A. Khan, D. Brown, N. Dhayagude, X. He and Y. Ni, “Sources, production and commercial applications of fungal chitosan: A review,” Journal of Bioresources and Bioproducts, 2022.

[88] H. Bojorges, A. López-Rubio, A. Martínez-Abad and M. J. Fabra, “Overview of alginate extraction processes: Impact on alginate molecular structure and techno-functional properties,” Trends in Food Science & Technology, 2023.

[89] J. Wang, S. Liu, J. Huang, K. Ren, y. Zhu and S. Yang, “Alginate: Microbial production, functionalization, and biomedical applications,” International Journal of Biological Macromolecules, 2023.

[90] G. Cattelan, A. G. Gerbolés, Ruben Foresti, P. P. Pramstaller, A. Rossini, M. Miragoli and C. C. Malvezzi, “Alginate Formulations: Current Developments in the Race for Hydrogel-Based Cardiac Regeneration,” Frontiers in Bionengineering and biotechnology, 2020.

[91] M. Mokhtari and S. Meddah, “Allergic reaction following alginate impression taking,” International Dental Journal, 2024.

[92] W. N. S. Wan Ali and N. A. Ahmad Tarmidzi, “A Rare Case of Contact Allergy towards Impression Compound Material,” European Jopurnal of Dentistry, 2021.

[93] European Union, “Blue bioeconomy,” 2025.

[94] R. Araújo, F. V. Calderón, J. S. López, I. C. Azevedo, A. Bruhn, S. Fluch, M. Garcia Tasende, F. Ghaderiardakani, T. Ilmjärv, M. Laurans, M. Mac Monagail, C. Peteiro, C. Rebpurs, T. Stefansson and J. Ullmann, “Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy,” Frontier in Marine Science, 2021.

[95] L. Perreira, L. Morrison, P. S. Shukla and A. T. Critchley, “A concise review of the brown macroalga Ascophyllum nodosum (Linnaeus) Le Jolis,” Journal of Applied Phycology, 2020.

[96] X. Shang, “The Current Status and Future Trends of Wearable Devices,” Applied and Computational Engineering, 2024.

[97] A. Akter, M. M. H. Apu, Y. R. Veeranki, T. N. Baroud and H. F. Posada-Quintero, “Recent Studies on Smart Textile-Based Wearable Sweat Sensors for Medical Monitoring: A Systematic Review,” J. Sens. Actuator Netw., 2024.