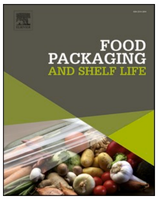
Food Packaging and Shelf Life 40 (2023) 101224

Contents lists available at ScienceDirect

Food Packaging and Shelf Life

journal homepage: www.elsevier.com/locate/fpsl



Pectin as a biopolymer source for packaging films using a circular economy approach: Origins, extraction, structure and films properties

Ian P. Butler [a,b,*], Russell A. Banta [a,b], Andrey A. Tyuftin [a], Justin Holmes [b], Shivani Pathania [c], Joe Kerry [a]

[a] *Food Packaging Group, School of Food & Nutritional Sciences, University College Cork, Cork, Ireland*
[b] *Environmental Research InstitUte, Lee Road, University College Cork, Cork, Ireland*
[c] *Teagasc, Ashtown Food Research Centre, Ashtown, Dublin 15, Ireland*

ARTICLE INFO

Keywords:
Pectin
Structure
Properties
Application
Packaging
Circular economy

ABSTRACT

The world currently faces a looming crisis, with both energy production and packaging manufacturing inextricably tied to the availability of oil. No biomaterial exists with sufficient universal properties to replace synthetic plastics. To date, research into renewable materials has remained largely focused on a select few biopolymers. Current research into the next generation biomaterials focuses on existing, sustainable, waste streams as a source of renewable polymers. Pectin, the focus of this current review, is a relatively cheap, widely available polysaccharide, usually extracted from apple pomace and fruit extracts. While widely employed in food products as a hydrocolloid, pectin has still not been widely investigated as a potential packaging material. In this review, the structure of pectin and its extraction are outlined, and the future of pectin within the compostable packaging field is established. The ramifications of failing to address the correct environmental measures and achieve a balanced carbon cycle are unavoidable. Identifying and utilizing what is currently described as waste or underutilised, yet sustainable, materials which could reduce our dependence on oil is crucial. The established position of pectin in the food industry, and its processability on a commercial scale, give pectin significant advantage over alternative biopolymer materials for potential use in food packaging applications.

1. Introduction

Synthetic plastics are predominantly produced using petroleum (which is finite and non-renewable) (Tokiwa et al., 2009). While many plastics may be recycled in theory, in practise, contamination arising from disposal of plastic by food waste prevents the cost-effective recycling of these materials. An unsustainable amount of recyclable plastic at the end of its life-cycle ends up in the landfills, the environment, or incinerated for energy and disposal (Song et al., 2009). By 2040, it is estimated that plastic pollution will triple in our oceans. With 85% of marine litter comprising of plastic. This means that 23–37 million metric tons of plastic will be added to the ocean annually (United Nations, 2021). As of 2014, the economic burden accrued by marine ecosystems was $13 billion (United Nations, 2014). By 2050, the world population is estimated to reach 9.7 billion (United Nations, 2019). A growing population, and subsequent growth of the food packaging industry, has put the issue of sustainability to the forefront of minds worldwide.

Society heavily relies on a non-renewable, finite resource (oil) to produce plastics. Plastic packing lifetimes are hundreds of times longer than that of the foodstuff it protects. Additionally, core issues exist such as; **1)** plastic packaging being destroyed during use; **2)** the inability to recycle certain plastics, co-extrusions, laminates; **3)** lack of consumer engagement in recycling; **4)** the unpleasant appearance, odour, and taste of plastic alternatives **5)** the cost associated with newly developed sustainable packaging sources, and the lack of governmental and legislative support for their development, **6)** early poor evidence of recycled plastic stability in new packaging structures. Critical items (water, food, medicine, etc.) rely primarily on plastic packaging for protection during transport and long-term storage, primarily owing to its cost, light weight, and versatility. Without renewable alternatives, many industries will not be able to support the increased demand for vital products into the future and, this will being particularly so for products moving over extended distribution chains.

Human activities are undeniably the main driving force for the current climate crisis, as detailed by the latest Intergovernmental Panel on Climate Change (IPCC) report. A growing population is resulting in

---

* Correspondence to: Food packaging group, FNS, University College Cork, College Road, Cork, Ireland.
E-mail address: Joe.Kerry@ucc.ie (I.P. Butler).

https://doi.org/10.1016/j.fpsl.2023.101224
Received 21 September 2022; Received in revised form 9 November 2023; Accepted 19 November 2023

an exponential increase in these numbers. Currently, the land and ocean retain 56% of CO_2 emissions annually generated by human activities (Masson-Delmotte et al., 2021). By finding ways to repurpose waste, the environmental damage of current technologies can be limited and waste as a phenomenon eliminated. Finding alternative uses for biomass-derived food waste streams, such as Apple Pomace (A.P.) and fruit extracts as simple examples, is a crucial step in moving processing as a whole to a more sustainable operation and forming more sustainable, circular economy.

While polysaccharides such as cellulose, starch, and chitosan have been extensively investigated as biodegradable packaging materials, pectin remains underutilised. Considering pectin's low cost, availability, film forming properties, and the large quantity produced from waste annually, this is surprising. In combination with its widespread use in the food industry, pectin's film forming properties make it a promising candidate for future material development. Irrespective of the polysaccharide being used to produce biodegradable packaging, it is clear to see that research into next generation packaging systems involves producing polymers and textiles from arising agricultural wastes. Achieving this is vital to attaining a greener and more circular economy. Pectin is typical extracted from citrus peels, apple pomace, and sugar beet pulp. Abundantly present in the cell wall and middle lamella of plant sources, pectin is a heteropolysaccharide containing an α-1–4 linked D-galacturonic acid (GalA) rich backbone. Pectin can further be subdivided into three separate domains which will be looked at in detail later in this review: homogalacturonan (HG), rhamnogalacturonan I (RG-I), and rhamnogalacturonan II (RG-II) (Cui et al., 2021).

While synthetic plastics present numerous short-term benefits, pollution due to their incineration makes plastics the 2nd largest contributor to greenhouse gases. In the U.S., this results in approximately $13 billion in financial damage every year (Sid et al., 2021). In Europe, 38% of plastic production is for use in the packaging sector (Hahladakis et al., 2018). The use phase for 60% of plastics circulating in society today is between 1 and 50 years (Plastics Europe, 2020). Plastics are comprised of various reactive, toxic chemicals, and can accumulate in the upper trophic levels, resulting in their consumption by humans (in the form of microplastic contaminants). The burning of municipal plastic waste can release halogens (Rajmohan et al., 2019), carbon monoxide, and heavy metals (Cheng et al., 2020). The replacement of polyethylene (PE), polystyrene (PS), and polypropylene (PP), along with several other petroleum-based plastics, is a primary focus of polymer chemists. This is due to each plastic's individual contribution to environmental pollution, due to inadequate disposal and treatment of food packaging (Zhang et al., 2021). Several health issues (including cardiac malfunction, respiratory issues, damage to the liver and kidneys, nausea, vomiting, as well as reproductive problems) have been linked to the inadequate disposal of PS alone (Rajmohan et al., 2019).

There are two main classifications of biopolymer food packaging. The first is *compostable packaging*, manufactured with specific biodegradation and composability properties in mind (i.e., solubility of the material, composability of the material at different temperatures and humidity, etc.) (Tyuftin & Kerry, 2021). The second type of food packaging, *edible films*, are comprised of edible biopolymers which may be consumed with the food product it packages. These biopolymers are either wrapped around the food product or deposited on top of the product as a thin film coating. In food items, these materials prevent lipid migration, and provide resistance to moisture (Chakravartula et al., 2019). Unlike traditional packaging, food products encased in these edible films produce no packaging waste. Proteins (e.g., collagen, gelatin), and polysaccharides (e.g., alginate, starch, various gums and chitosan) are typically employed in edible films and packaging. As these packaging forms are all derived from food sources, there is a limited pool of materials to choose from, curtailing the development of edible films to some degree. To meet the anticipated demand for edible films, existing waste sources of generally regarded as safe (GRAS) index biopolymers needs to be examined. Producing novel polymers from such waste streams not only adds value to waste materials (by creating additional revenue streams), but also reduces food waste generated during food processing and consumption. As edible films can be produced using pectin extract sourced from existing waste streams, it is an ideal candidate for further investigation.

The increase of research into environmentally-conscious packaging reflects the shift expected of the packaging sector by society at large. Overall, work in this field hopes to shift the production of short-shelf-life products from exhaustible and environmentally-unfriendly polymers, to more sustainable, environmentally-friendly alternatives. In short, disposable food packaging that far outlives the item it serves but in a functional and aesthetic manner should be derived from renewable waste streams, with a lifespan appropriate to its purpose. Therefore, the objective of this review is to evaluate pectin as a potential bio-sourced polymer to produce renewable, environmentally-friendly packaging, aligned with the circular economy concept.

2. Literature methodology

The initial research for this review surrounded circular economy concepts, and how plastic food packaging is negatively impacting the environment. Global organisations such as the UN provide up to date statistics regarding these issues. After clarifying and understanding the current environmental challenges that face the food packaging industry as a whole, the biopolymer in question, pectin, was researched to determine potential sources, extraction techniques, and overall suitability to a circular economy initiative. The apple processing industry was quickly identified as being an abundant waste stream for pectin due to its waste disposal of A.P. post juicing and belt rejection processes. Given the high percentage of pectin present in A.P., typically between 10% and 15% (Vidović et al., 2020), this waste stream is an ideal candidate for implementation into a sustainable food packaging project. The Science Direct database was then utilised to evaluate the recent research and use of pectin in this field. After uncovering the surprising underutilisation of pectin, research was quickly directed to displaying how this natural biopolymer is currently extracted by industry and how these methods can subsequently be improved to achieve an overall 'greener', environmentally friendly process that can replicate and better current techniques. Maríc et al., 2018, was one of the papers originally selected to gain a well-rounded insight into this topic. From here pectin's structure, extraction processes, film forming capabilities and suitability were established. An overall conclusion in relation to this topic was subsequently formed from the in depth study of relevant literature.

3. The current and future state of packaging

3.1. Plastic usage and waste

Many concerns held by consumers in relation to products that use synthetic plastics include; health and toxicity issues caused by their; fabrication, use, and disposal; their non-biodegradable nature; and their utilisation of finite oil resources (Carvalho & Conte Junior, 2020). Non-renewable materials accounts for as much as 95–99% of all plastic materials being produced by petrochemical industries. The inability of microbes to degrade these plastics results in serious environmental damage (Seenuvasan et al., 2021). The carbon cycle is currently in a state of mass imbalance. This imbalance stems from the rate of consumption of finite synthetic polymer sources being far greater than the rate of replenishment of finite oil sources (Kijchavengkul & Auras, 2008). In 2010, global petrochemical-based plastic production exceeded 250 million tonnes. A total of 100 million tonnes of plastic was produced for the packaging industry, while only 125,000 tonnes of biobased plastic packaging material was produced (Robertson, 2013). This is less than 0.5% of the current plastic market, and 0.125% of the packaging market. This large disparity between the production of synthetic plastic packaging and that made of biodegradable materials has a negative environmental impact.

Synthetic plastics can take 400-years to break down when placed in landfills. Plastic accumulation has led to serious environmental issues, providing the incentive to research alternative, compostable packaging (Sason & Nussinovitch, 2021). The production of packaging materials around the world is increasing at an annual rate of 8%. Ninety percent of plastic accumulation occurs in the environment with only synthetic plastics having a recycling rate of less than 5% (Beikzadeh et al., 2020). Unless more robust recycling methods are used to improve the amount of plastic recycled, products designed to degrade at end-of-life must be employed to reduce our environmental impact. An additional factor to consider is the development of a material designed to complete a specific task is much simpler than the design of a recycling infrastructure capable of dealing with a large variety of synthetic plastics, often blends, contaminated with food waste. This has led researchers to investigate a wider variety of biopolymers, to replace existing packaging which can be composted within food wastes without food separation from plastics.

Only a few, select biopolymers have been researched for their applications in packaging to date **(**Fig. 1**)**. Due to their hydrophilic nature, often "clever chemistry" is employed to improve the properties of these materials. While these processes use materials sourced from renewable streams, modifications to improve the biopolymers properties often render the material unsuitable for reintegration into the carbon life-cycle, as with these improvements comes longer degradation times and industrial by-products. These "renewable" materials can be as costly to the environment upon disposal as the plastics "green" materials target to replace.

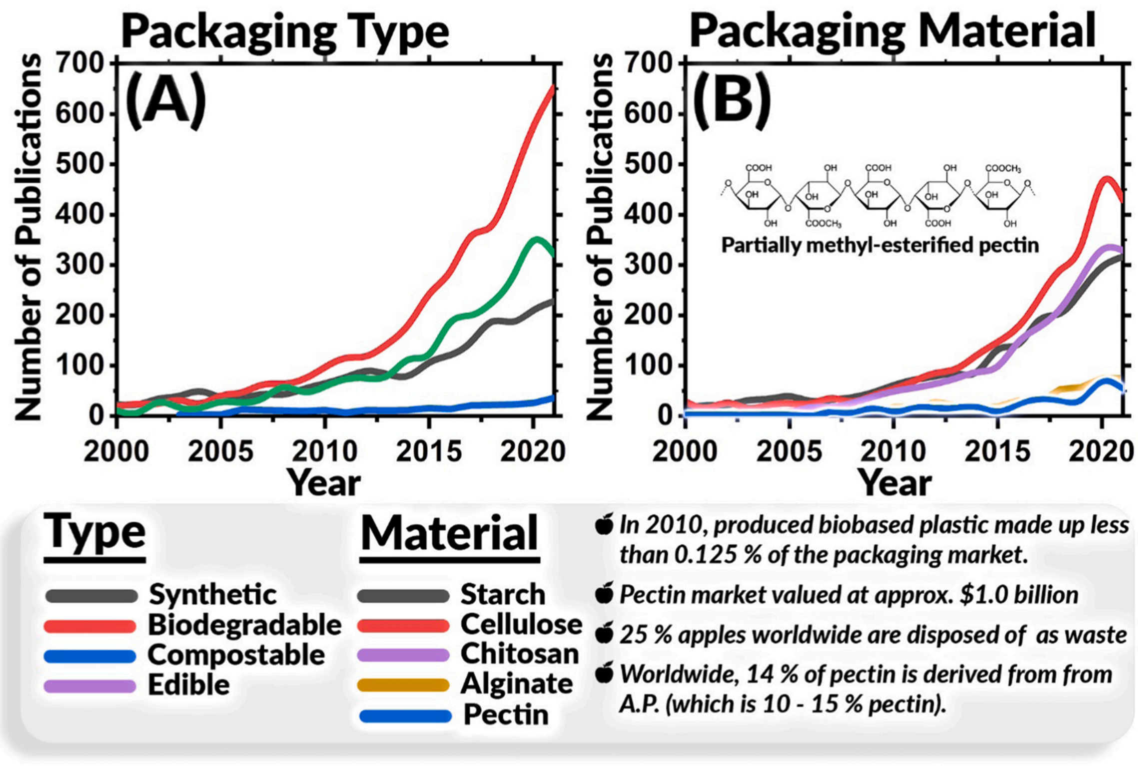
3.2. Bio-based circular economy

A circular economy is described by the European Commission as 'an economy that.

aims to maintain the value of products, materials and resources for as long as possible by returning them into the product cycle at the end of their use, while minimising the generation of waste'(Eurostat, 2021).

According to the United Nations (UN), global food waste is as large as 14%, with loss in the fruit and vegetables sector as producing up to 20% waste (United Nations, 2022). Approximately 30% of the food produced worldwide occurs as a loss at some level within the food supply chain (Oliveira et al., 2021; Santagata et al., 2021). BREXIT, the COVID-19 pandemic, instability in the oil market, and recent conflicts around the world, has only added to the strain on the industry due to the disruption of supply chains, and the closure of many businesses worldwide. Global food losses have compounding effects on the environment, and the economy (Santagata et al., 2021). The over-simplified solution to this problem is to reduce food losses and food waste, which can be achieved through the adoption of a truly circular economy. The Food and Agriculture Organization of The UN defines *food loss* as 'the decrease in the quantity or quality of food resulting from decisions and actions by food suppliers in the chain, *excluding* retailers, food service providers, and consumers'. *Food waste* differs from that, defined as 'the decrease in the quantity or quality of food resulting from decisions and actions *by* retailers, food service providers, and consumers'(FAO, 2022). For the purposes of this review, food waste will be defined as the loss of food at any point from production to consumption.

Throughout a food products lifecycle, food can become waste at any point. Biopolymers are a common waste found in both the agricultural and food sector. The large volume of food waste, such as apple pomace (AP), produced by industrial scale apple juicing for soft beverage and cider manufacture can be separated into 2 categories; **1)** the loss of apple through bruising or spoilage, that are declared as 'belt rejected' and; **2)** A.P. that is discarded after juice extraction. The production of AP from apple beverage processing is a clear example of a bioprocessing waste stream. In cider processing, AP is by far the most abundant by-product. Asturias (Spain) is one of the largest global producers of cider. Biannually, approx. 12,000 tons of AP is produced per 45,000 tons of apples (Calvete-Torre et al., 2021). Though biodegradable, the high-water content of the disposed AP causes various environmental pollution



- *In 2010, produced biobased plastic made up less than 0.125 % of the packaging market.*
- *Pectin market valued at approx. $1.0 billion*
- *25 % apples worldwide are disposed of as waste*
- *Worldwide, 14 % of pectin is derived from from A.P. (which is 10 - 15 % pectin).*

Fig. 1. **:** Publications corresponding to packaging materials over a period of 21 years. From SCOPUS database for years 2000–2021 (Source: https://www.scopus.com/).

concerns due to high chemical- and bio-chemical oxygen demand. The repurposing of pectin to produce renewable textiles would alleviate pollution caused by the disposal of both plastic and AP (Shalini & Gupta, 2010).

Given AP's high perishability, it must be dried before storage. While it may have promising film forming properties, the high evaporation temperature of water means this can be an energy-intensive or time-costly step. This may be some of the reasons for the limited development of pectin technologies from AP. AP is typically used for; pectin extraction; livestock feed; food products; fuel purposes; and biotransformation (Barreira et al., 2019). Considering all of the above, it is evident that the repurposing and upcycling of waste AP would be highly beneficial in both creating a greener, more circular economy, while taking an underutilised waste product and turning it into a valuable resource.

3.2.1. Biodegradability of pectin-based products

In order to achieve a truly circular economy using the above mentioned waste stream, the final product must be of a biodegradable and compostable nature. Therefore, pectin products must be shown to be capable of this. To date, a large amount of the knowledge gained surrounding pectin's breakdown has been garnered through oral delivery as pectin is commonly used carrier of drugs and other compounds in the medical field. Pectin's hydrophilic nature and ability to function in harsh environments (such as the stomach) make it an ideal candidate in this field. Pectin has also been implemented in wound healing as a result of being non-toxic, high availability, low cost, and generally being recognised as safe (GRAS) (Martau et al., 2019). However, at time of writing, very few studies have been undertaken to determine the compostability conditions required for the biodegradation of pectin films/edible films. Ren et al., 2022, displayed the biodegradation of pectin-based films incorporated with biodegradable polyvinyl alcohol, glycerol, and calcium propionate. Results showed that biodegradation occurred in the fixed range of 28 ± 0.5 ℃ and 50 ± 2% RH. Large amounts of microorganisms were detected after two weeks on natural soil, followed by significant biodegradation at three weeks, finally leading to complete biodegradation at five weeks. This study indicates the large biodegradation potential of pectin-based films on natural soil (Ren et al., 2022). However, more comprehensive research must be carried out to determine the exact conditions required for the compostability of pure pectin films to determine how environmentally friendly this process is.

4. Pectin

4.1. Pectin: sources and market

Over the past decade, there has been a considerable increase in research regarding the production of biodegradable packaging, particularly if they can be produced from existing waste streams. Within this field, pectin (a polysaccharide) has been a largely neglected. Given pectin's abundance as a waste product and its similarity in chemical terms to sodium alginate (a biopolymer capable of forming films and membranes on an industrial scale), this is surprising. The need to identify alternative uses for renewable waste streams, such as pectin, has never been more urgent, considering recent global warming concerns. A dramatic change in lifestyle within the coming decades is unavoidable if society continues to fail at addressing problems of climate change.

From production to consumption worldwide, approx. 33% of all food produced for human consumption is disposed of as waste (Boiteau & Pingali, 2023). Annually, total global edible food waste is responsible for 1.3 billion tonnes of 'primary product equivalents' (Arshadi et al., 2016). Vegetables and fruits are responsible for 14.8% of all food waste (Baiano, 2014). A significant producer of food waste is the apple processing industry, disposing of 25% of all apples harvested. AP accounted for 3600 kilotons of biomass worldwide in 2010 (Cho et al., 2019). AP is a highly concentrated source of pectin, the dry weight of AP accounting for 10 – 15% pectin (Vidović et al., 2020).

Pectin is a heteropolysaccharide, found abundantly in nature as a key structural component in plant cell walls. Pectin is a major by-product of the fruit and vegetable processing industry, used in many food products (including jams and candies). Pectin is obtained on an industrial level through various extraction techniques, from either AP or citrus peels (Espitia et al., 2014). Due to pectin's low cost, wide availability, biodegradability, non-toxicity, and biocompatibility (Lei et al., 2019), pectin has recently gained attention as a new potential material in the formation of edible films, in particular **(**Fig. 1**)**.

As it can be seen from Fig. 1, while pectin is an extensively used polymer in the food industry in relation to jams and confectionary products, it is surprisingly underutilised in the food packaging sector. With the somewhat exponential rise in biodegradable packaging research in the past decade (A), it should be expected that a versatile and abundant biopolymer such as pectin would follow this trend. However, this has not been the case (B). Nevertheless, recently the global market for pectin has seen significant increases.

Throughout the global hydrocolloids market, pectin has become an increasingly popular functional ingredient in many areas, including edible packaging (Marić et al., 2018). Globally, in 2020, an estimated value of $2659.59 million was invested in the edible films and coating market, forecast to undergo a compound annual growth rate of 7.64% from 2022 to 2027. At 230 million metric tons per year, plastic consumption today is almost forty-six times higher than in the 1950′s (Mordor Intelligence, 2021). In 2019, the estimated market value of pectin was valued at approximately $1.0 billion, forecast to undergo growth of 6.5% annually until 2025 (Markets and Markets, 2019).

4.2. Pectin polymer structure

Pectin is a structural component in plant cell walls and is one of Earth's most abundant polysaccharides. As previously pointed out, this polymer is typically obtained from plant and fruit sources (Shafie et al., 2020). Pectin is easily biodegradable, and largely water soluble (Dash et al., 2019). Structurally, pectin may be considered as block copolymers consisting of two polymers, a homopolymer (Block A) and a heteropolymer (Block B) **(**Fig. 2**)**. Each block has unique chemistries which contribute overall to pectin's physiochemically characteristics. Block A, Homogalacturonan (HG), is a linear, homopolymer backbone, consisting of galacturonic acid (GalA) units. This block of pectin is known as the 'smooth' region because of its linear appearance. Block B, Rhamnogalacturonan I (RGI), is a heteropolymer, consisting of a repeating GalA and rhamnose disaccharide backbone. This block of pectin is referred to as the 'hairy' region due to its branched appearance (M. Chen & Lahaye, 2021). A total of 65% of the total structure of pectin exists as consecutive GalA with neutral monosaccharide side chains (Cho et al., 2019). These GalA units are linked at positions O-1 and O-4 (Mohnen, 2008). Pectin's structure can be seen to have slight variations, depending on a number of factors, including; source; metabolic development stages of the fruit; growth environment; and extraction procedures. It has been notably challenging for researchers to examine pectin's full structure. However, each domain within pectin has been extensively examined (Round et al., 2010).

HG is the most prominent pectinous domain. It's backbone, a homopolymer (i.e. a repeating monosaccharide α-1,4-linked-D- GalA), makes up approx. 50–70% of primary cell wall pectin (Shafie et al., 2020). Of all pectic domains, HG is the most detailed and understood **(Figure 2)**. RG-I is a heteropolymer, and accounts for 20–35% of pectin. It consists of a repeating GalA and rhamnose disaccharide backbone. This backbone is accompanied by neutral side chains which are attached at the O-4 position and occasionally attached at the O-3 position of α-L-Rhap backbone units (Willats et al., 2001). Rhamnogalacturonan II (RG-II) is largely referred to as having the most complex structure of all pectin domains. It consists of a homogalacturonan backbone, aligned

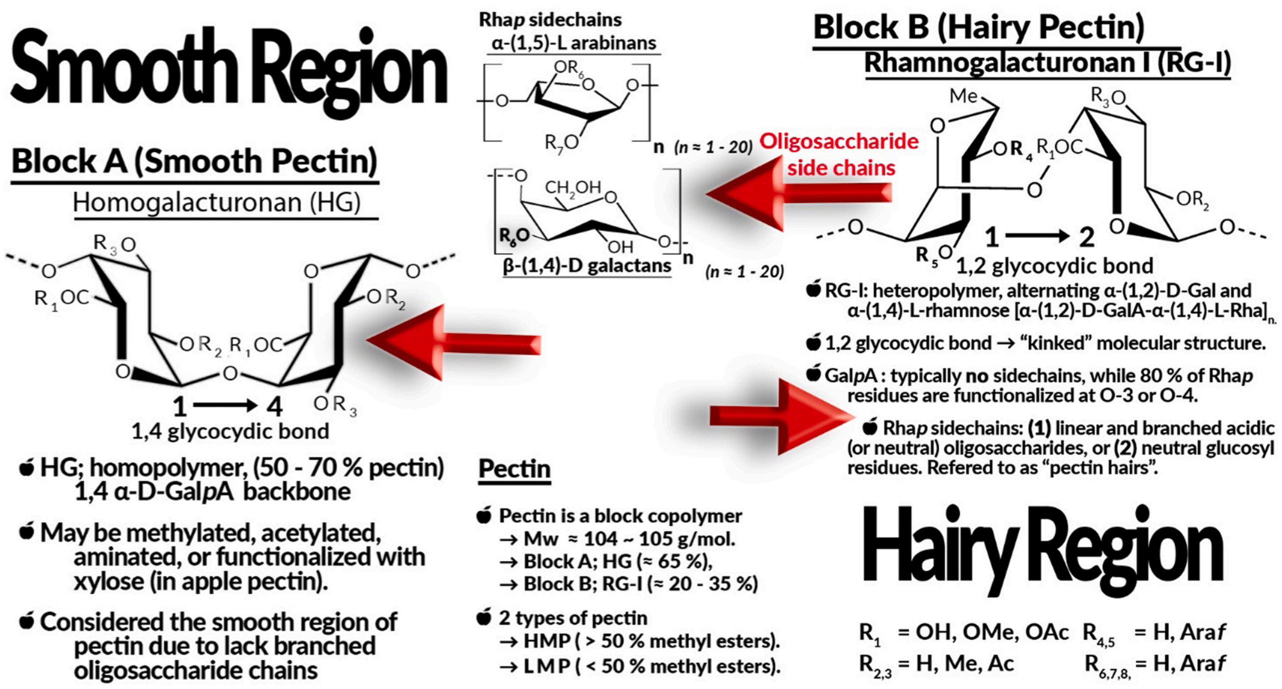


Fig 2. (A, left) Details characteristics and physicochemical properties of smooth pectin (i.e., pectin missing RG-I domain. **(B, right)**. Details characteristics and physicochemical properties of hairy pectin (i.e., containing RG-I).

with several side chains composed of Rha, and other neutral sugars (Marić et al., 2018). Despite the similarities in their naming, RG-II and RG-I do not have related structures (Willats et al., 2001). RG-II accounts for roughly 10% of pectin, and typically is present in plant walls as RG-II dimers.

As mentioned previously, different domains in pectin are often referred to as having a 'hairy', or 'smooth', appearance. The smooth region of pectin is composed of HG, while the hairy region of pectin's structure consists of RG-I, RG-II, and xylogalacturonan (XG) (Celus et al., 2018; Mao et al., 2019). These hairy regions have high probiotic potential, making pectin a good candidate for edible film technologies. Therefore, during the extraction process of pectin, high recovery of these regions is widely regarded as being more important than the recovery of smooth regions (Shivamathi et al., 2019).

Pectin's main application in the food industry stems from the texture and mechanical properties it possesses, making it invaluable for confectionary products (jams and jellies). Other such applications include desserts, bakery, and dairy products (Reichembach & Lúcia de Oliveira Petkowicz, 2021). The thickening and gelling properties of pectin are largely influenced by the degree of esterification (DE), degree of methylation (DM), and the GalA content. The DE of pectin may be defined as the total percentage of carboxyl groups that are esterified with methanol (Marić et al., 2018). Alternatively, the DE has been defined as being the percentage of esterified GalA, out of the total GalA residues, and usually represents the degree of methylation (DM) (Mu et al., 2017). On extraction from the cell wall, the conditions by which the extraction takes place have a big influence on the DM of pectin (Reichembach & Lúcia de Oliveira Petkowicz, 2021).

Pectin isolates can be divided into two groups based on their degrees of methylation: high methoxyl pectin's (HMP) and low methoxyl pectin's (LMP). HMP's have a DM that is $\geq$ 50% while LMP's will have a DM that is $<$ 50% (Chan & Choo, 2013). Contrasting physio-chemical properties result from differences in the molecular structure of HMP and LMP, producing materials with different processing requirements. HMP will have the capability of forming a gel within an acid-based system (pH 2.0–3.5), with high concentrations of sugar, or sorbitol, of between 55% and 75%. LMP will form a gel over a wider pH range (2–6 pH) while not requiring the presence of sugar (Hosseini et al., 2016).

Pectin production from AP accounts for approximately 14% of all pectin production around the globe (Morales-Contreras et al., 2020). Pectin's composition is largely determined by the source from which it was isolated, and purification conditions. Differentiations in pectin's chemical structure typically results from the polygalacturonic acid backbone having esterified groups being distributed differently. Pectin's that are extracted from apple sources can have at least 80% esterification, and therefore can form a highly viscous gels (Dranca et al., 2020a). However, these polymers are exposed to pectinolytic enzymes after apple processing, which causes their quick depolymerisation and de-esterification in AP. Therefore, the drying of AP immediately following pressing is crucial to limit these deteriorative processes (Barreira et al., 2019).

4.3. *Pectin extraction*

4.3.1. *Generalities*

Extraction technique, and the source from which it is extracted, largely determine the quality and yield of pectin. Preforming extraction procedures at the commercial conditions listed above requires the usage of harsh chemicals. This creates harmful wastewater and requires high energy inputs, leading to several environmental problems (Shivamathi et al., 2019). Harsh acids such as HCl, lactic acid, and nitric acid give good extraction results and high yields of insoluble pectin that has been tightly bound to the plant cell matrix. Alternatively, sodium hydroxide, or enzymes, may be used to extract pectin (Sandarani, 2017). However, the negative environmental implications of using acids, along with the emergence of greener techniques, have led to shifts in the techniques used to extract pectin. Additionally, pectin extracted using such acids would not hold the right to be supplied as clean labelled ingredients. This further encourages the search for greener, environmentally friendly, and sustainable alternatives.

4.3.2. *Pectin extraction studies*

After apples have been juiced, waste pomace is dried (typically air-dried) at elevated temperatures. This dry pomace is ground into a flour (which consists of high surface area AP particles). Pectin is extracted from this flour using acidic treatment (< pH 3). This process usually takes place at elevated temperatures (60–100 °C), under continuous agitation, for extended periods of time (0.5–6 hrs) (Koubala et al., 2008). Pectin is then precipitated (using a crosslinking agent or non-solvent) and filtered. The filtrate is then washed to remove contaminants (Fig. 3). Harsh extraction treatment can result in damaged pectin and a reduced yield. Obtaining high quantities of undamaged pectin using green extraction techniques is essential, if pectin is to be adopted as a replacement to petrochemically derived packaging and conform to a circular economy approach.

Conventional extraction (using HCl) results in; the loss of volatile compounds; environmental damage; and the degradation of many valuable compounds within AP (such as flavonoids). More recently, use of green organic acids for food extractions, such as citric, acetic, and malic acid have increased in utilisation (Cho et al., 2019; Ma et al., 2013; Marić et al., 2018). The use of these greener solvents over traditional HCl lowers hydrolysing capacity during extraction, resulting in lower depolymerisation values in extracted pectin. Gentler extractions also prevent the degradation of valuable flavonoids during the wash stage, allowing for waste generated during extraction to be recovered and resold.

Microwave-assisted- extractions (MAE) have been employed for pectin extraction from AP due to the poorer efficiency of other extraction methods [e.g., Ultrasound-assisted extraction (UAE) and Enzyme-assisted extraction (EAE)] (Dranca et al., 2020b). While MAE yields may be similar to solvent extraction, MAE offers far superior extraction times. Solvent extraction performed using citric acid (1.5–2.5 pH, 70–90 °C) and MAE (280–560 W) produced similar yields under optimum conditions (pH 1.5, 38.91% and 38.06% yield, respectively). However, MAE offers extraction times 80-times faster (90 s) than solvent extraction alone (120 min). Pectin yield increased with increasing solvent extraction temperatures, lower pH values, or MAE operating power levels (Dranca et al., 2021).

Elevated extraction temperatures produce superior pectin yields, with room temperature extractions achieving far lower yields than extractions using boiling water (12% and 33–38%, respectively). Extractions at these elevated temperatures also produce less viscous pectin solutions, indicating a pectin extract with a lower molecular weight and less “hairs”(Basanta et al., 2012). Similarly, extracting pectin from cocoa husks using citric acid (2.5 pH) at elevated temperatures improved pectin yield from 3.58% to 5.66% (for 50 °C and 95 °C extractions, respectively). These results were compared against traditionally used HCl at the same temperatures and pH ranges, where the highest yield achieved was 5.23%. The increase in yield is attributed to the higher temperature being capable of more efficiently solubilising pectin present in the cell wall. Again, increasing the extraction time from 1.5 to 3.0 hrs increased pectin yields, from 5.66% to 7.62% (Chan & Choo, 2013).

Similar results have been noted with the extraction of pectin from sugar beet pulp. When comparing organic acids (citric, malic, and lactic acid), regardless of the acid used, pectin yield was approx. 7% greater at pH 1.5 than at pH 2.0. It was concluded that the pH of the solvent plays a pivotal role in cell lysis, releasing pectin into solution for extraction. Again, increasing extraction time from 1 to 2 hrs had a similar effect, increasing pectin yield by approximately 4%. Overall, citric acid (the best performing organic acid) achieves similar extraction yields to HCl (17.2% and 18%, respectively). These results positively promote the upscaling of organic acid extraction of pectin in the future (Ma et al., 2013).

Similar research has confirmed that organic acids (malic, citric, and tartaric) could be used effectively for pectin extraction from AP waste. At both low (0.1 M) and high (1.0 M) organic acid concentrations pectin yield was comparable to HCl extraction. The highest preforming organic acid was tartaric acid (1.0 M), yielding 6.2% pectin isolate compared to HCl (6.4%). These results demonstrated that pectin can be extracted with greener solvents without compromising pectin yield. This is vital, as any reduction in yield at an industrial scale would result in additional waste and revenue loss. Pectin obtained using organic acids had a larger molecular weight (m_w) than pectin extracted using HCl. The use of low concentration organic acids is a viable solution to the pollution and environmental damage caused by employing mineral acids commercially (Cho et al., 2019). As discussed earlier, the quality of the pectin (“hairiness”, m_w, methoxyl and ester content) relies heavily upon the extraction procedure. Therefore, avoiding solvents which reduce the m_w

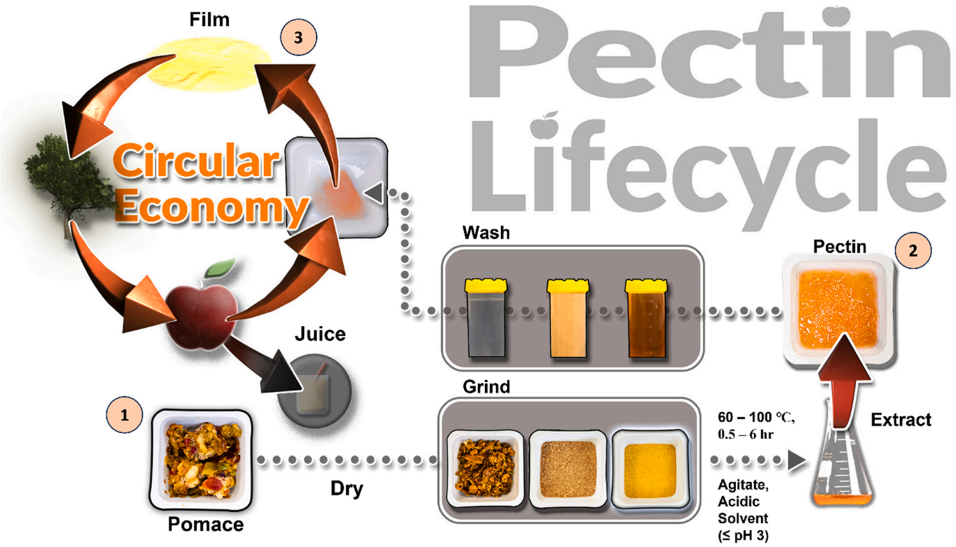


Fig. 3. Pectin processing and extraction from apple waste source. Apples are harvested from orchard, with approx. 25% lost due to belt rejection. **(1)** Apples are juiced, producing apple pomace. Pomace is dried and ground to produce high surface particles, suitable for pectin extraction. Pectin “flour” is treated with an acidic solvent (mineral, organic, etc.), at an elevated temperature (60 – 100 °C) for several hours (0.5 – 6 hr) under agitation. Waste pomace after pectin extraction is removed waste is removed through filtering or centrifugation, and the pectin precipitated via using a non-solvent **(2)**. Precipitated pectin is then washed to remove extraneous compounds (contaminants, flavonoids, residual acid, etc), and subsequently dried for storage. **(3)** Pectin textiles are produced, which may be used as compostable feed for agriculture.

of pectin via depolymerisation, thus removing pectin "hairs", is vital when considering pectin as a packaging material.

Cui et al., 2021, outlined common extraction techniques for pectin from apple sources and identified the advantages and disadvantages of using such methods (Fig. 4).

5. Pectin-based film formation

5.1. Phase separation

Before outlining the conditions necessary for pectin to form compact, cohesive films, the phenomenon that is phase separation must be outlined to understand film formation. Films that consist of two or more components within a matrix, undergo phase separation. This process plays a key role in the formation of such films. Obtaining a detailed understanding of phase separation allows for the creation of edible films that will possess the required properties of a food packaging system. As outlined by Petersson, Lorén & Stading, 2005, in a solution that consists of two polymers, three outcomes can unfold; **(1)** a homogenous phase; **(2)** the solution is split into two phases due to the polymers separating; **(3)** association of both polymers, leading to precipitation or gelation.

In the early stages of phase separation, it can largely be described as the solution undergoing a continuous change in the composition of phases. While this change is happening, the spacing of the morphology of the phases stays constant (Reich & Cohen, 1981). The occurrence of phase separation within polymer blend solutions, is a result of the undiluted mixture being above the glass transition temperature of the system. Alternatively, this can be because of the evaporation of the solvent from solution. This process can lead to several different morphologies within the film structure. Bi-continuous structures can form, or island and holes may appear. These structural changes come from alterations in composition, $m_{w,}$ the thickness of the film, solvent changes, or external factors (Xue et al., 2012). Nucleation and growth, along with spinodal decomposition are two different processes associated with the phase separation in mixed biopolymer systems (Lorén & Hermansson, 2000). Through the control of these processes, it is possible to alter film structure and properties to best suit the desired application of edible films (X. Chen et al., 2020). However, if phase separation takes place in an un-controlled manner, it can result in defective film formations, which can have a negative effect on a films mechanical and barrier properties.

5.2. Pectin film forming conditions

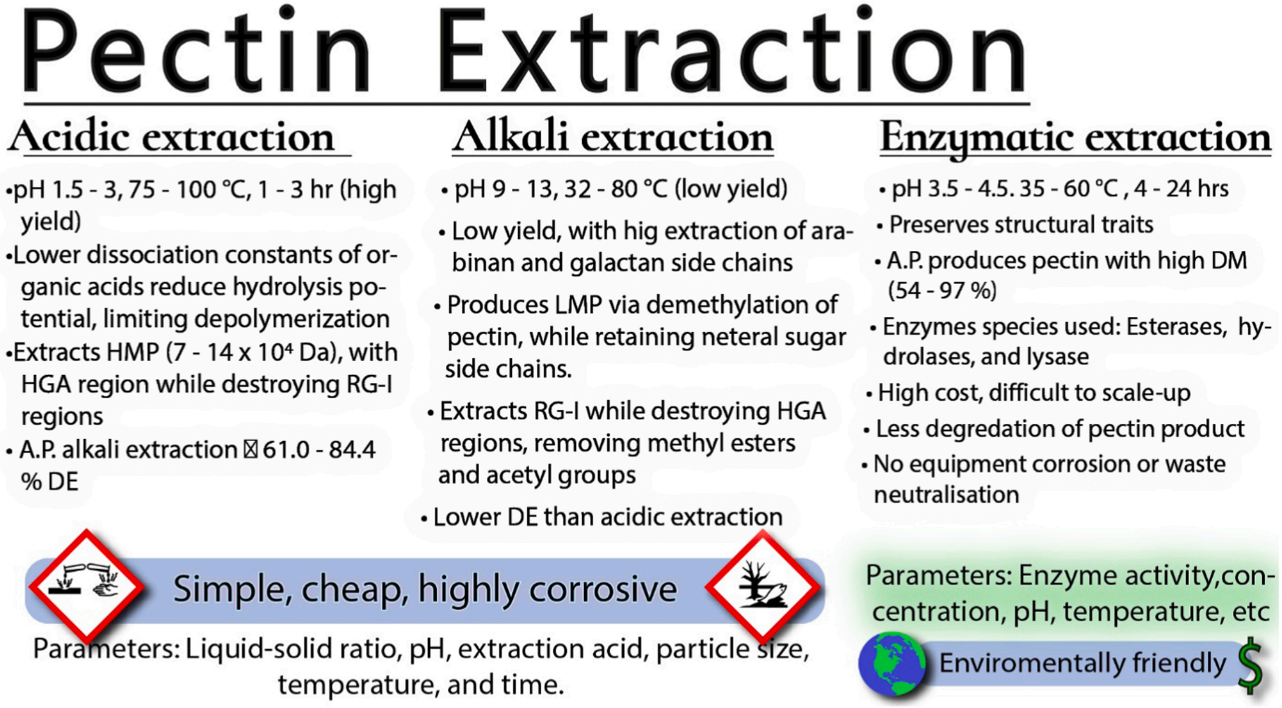
Pectin will have different physiochemical properties depending on plant source and extraction conditions employed. Therefore, it is understandable that different pectin's will have different film forming capabilities.

HMP's form gels when the water activity is lowered, requiring $> 55\%$ (w/v) co-solutes for HMP to form a physical gel (Munarin et al., 2012). This usually involves the addition of sucrose at low pH values (<3.5 pH). Cross-linking occurs between two or more pectin molecules, and forms junction zones throughout the gelation process (Fig. 5). The bonds that stabilise these zones are ones of weak interactions, such as hydrogen and hydrophobic bonds. These connections typically occur between polar and non-polar methyl esterified groups. The gels that are formed during the HMP's gelation process are thermally-reversible.

In contrast, negatively charged LMP's form gels through divalent cation bridging (e.g. employing Ca^{2+}) through electrostatic interactions, over a wide pH range (2.0–6.0 pH). Sucrose is not required to be present. LMP gelation process follows an 'egg-box' conformation as shown in Fig. 5. The *higher* the pH of the LMP solution, the *more* Ca^{2+} is required for crosslinking (J. Visser A.G.J. Voragen, 2009). Gelation in LMP's is influenced by several factors. While some factors are *intrinsic* (such as pectin structure, chain lengths, number of side chains, distribution of methyl esters, acetylation, and amidation), other controllable factors are *extrinsic (*such as pH, pectin content, temperature, calcium ion content, and sugar content (Fraeye et al., 2010; Galus & Lenart, 2013).

Higher m_w pectin's will typically form gels with compact networks. These networks exhibit high levels of viscosity and mechanical strength. Pectin's that have a m_w of < 10 kDa will not possess strong, compact structures due to a lack of Ca-binding sites (Cao et al., 2020).

Using a low pectin concentration increases the chances of ionic bonds forming within a single chain, inhibiting interchain binding and



Pectin Extraction

Acidic extraction

- pH 1.5 - 3, 75 - 100 °C, 1 - 3 hr (high yield)
- Lower dissociation constants of organic acids reduce hydrolysis potential, limiting depolymerization
- Extracts HMP (7 - 14 x 10^4 Da), with HGA region while destroying RG-I regions
- A.P. alkali extraction ⊠ 61.0 - 84.4 % DE

Alkali extraction

- pH 9 - 13, 32 - 80 °C (low yield)
- Low yield, with hig extraction of arabinan and galactan side chains
- Produces LMP via demethylation of pectin, while retaining neteral sugar side chains.
- Extracts RG-I while destroying HGA regions, removing methyl esters and acetyl groups
- Lower DE than acidic extraction

Simple, cheap, highly corrosive

Parameters: Liquid-solid ratio, pH, extraction acid, particle size, temperature, and time.

Enzymatic extraction

- pH 3.5 - 4.5. 35 - 60 °C , 4 - 24 hrs
- Preserves structural traits
- A.P. produces pectin with high DM (54 - 97 %)
- Enzymes species used: Esterases, hydrolases, and lysase
- High cost, difficult to scale-up
- Less degredation of pectin product
- No equipment corrosion or waste neutralisation

Parameters: Enzyme activity,concentration, pH, temperature, etc

Enviromentally friendly $

Fig. 4. acid vs base vs enzyme extraction techniques of pectin from fruit sources.(Cui et al.,; 2021).

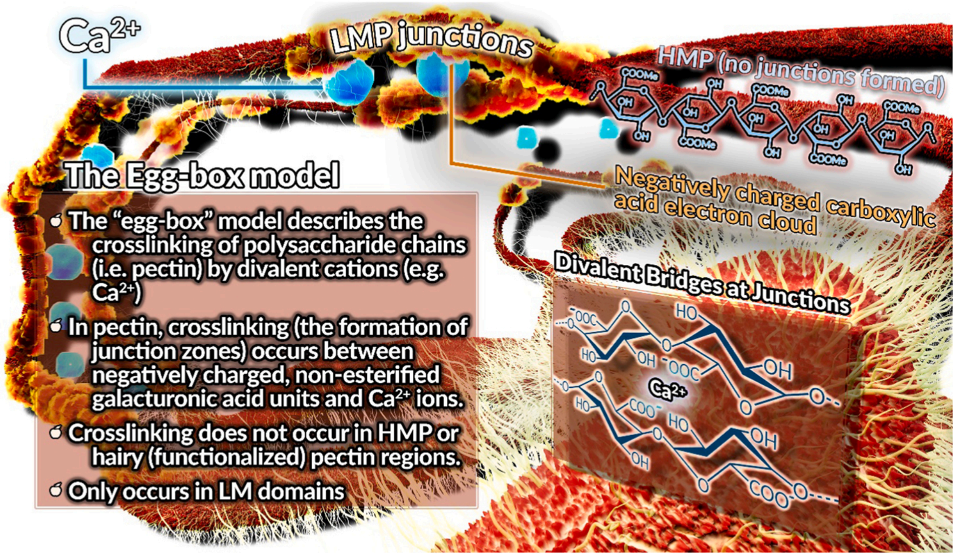


Fig. 5. **:** Schematic representation of the "egg-box" model for junction zone formation in pectin-calcium gels. 58,63.

preventing pectin network formation. Increasing pectin's concentration promotes the gelling process by providing a sufficiently dense mesh of junction zones (Fraeye et al., 2010).

5.3. *Film casting procedure*

Carbohydrate polymers have been widely researched as possible candidates for the formation of compostable, edible films (Dash et al., 2019; Espitia et al., 2014; Pirsa, 2020; Shafie et al., 2020; Shih & Zhao, 2021)· Lab-scale film production (Fig. 6) is typically determined by a five-step process; **1)** solubilisation; **2)** casting; **3)** solvent evaporation; **4)** film formation and; **5)** drying (Suhag et al., 2020).

1) Solubilization: Biopolymers (which are hydrophilic, i.e., bind and retains water) are often dissolved in aqueous buffers. (i.e., non-volatile solvent with slow evaporation rate) for dissolution and casting (Figure 6–1) (Jeya Jeevahan et al., 2020; Velaga et al., 2018). Additives such as plasticizers or crosslinkers may be used to improve a films property and promote network formation (Hoagland & Parris, 1981).

2) Casting: Biopolymer solutions are cast on materials hydrophobic enough to promote delamination (film removal) but not solution dewetting, which can negatively affect film formation (L. Z. Wang et al., 2007). The film may be cast as a single layer or as a laminate (Hoagland & Parris). Film deposition thickness controls many of a film's properties (mechanical, barrier, optical, etc.). WVP of pectin films can be optimized further through careful consideration of casting conditions. Casting *thick films* of linear branched pectin (with *small branch* sizes) encourage large amounts of plasticizer (water) to bind to pectin. This lubrication reduces pectin-pectin chain interactions, increasing the interpolymer spacing in the pectin network. This allows the uptake of more water. *Thin films* containing the *highly branched* source of pectin display tight intermolecular bonding between pectin chains. Close association between pectin chains leaves little room for plasticizer or water to enter the pectin matrix, resulting in thinner films with less WVP (Shafie et al., 2020).

3) Solvent Evaporation: Biopolymer solvent is removed. Biopolymer film production often encounters challenges here. Solvent evaporation must be carried out in a controlled environment (i.e., temperature and humidity), to prevent unwanted microstructural formation (Figure 6–3). As aqueous solvents require longer drying times than organic solvents, biopolymer film formation is a lengthy process (L. Z. Wang et al., 2007). Elevated temperatures may be used to improve film formation time, though if implemented, add additional costs to film production due to higher energy costs (Cai et al., 2020). This increase in

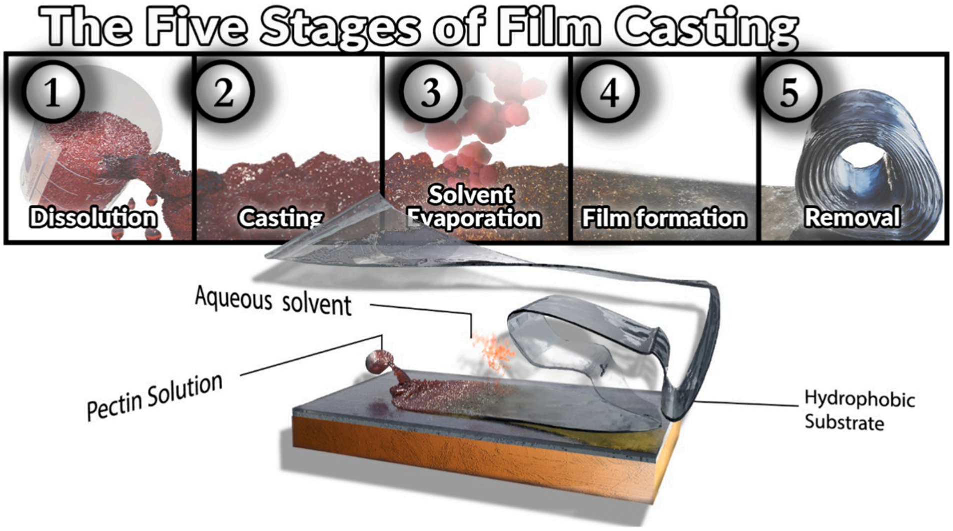


Fig. 6. **:** *Lab casting method for the formation of films.*

energy use can negate the environmental benefit of using an aqueous solvent (L. Z. Wang et al., 2007). Finally, biopolymer solution drying times increase with increasing ambient humidity. This increased drying time results in slower film production. Longer drying times also allow for longer periods of biopolymer phase growth after its phase separation from water, which ultimately controls a films morphology, and thus, it's mechanical and barrier properties.

4) Film Formation: Cast biopolymer is either 1) submerged in non-solvent to promote phase inversion or 2) dried until biopolymer transitions from liquid to solid phase.

5) Drying: Film is removed from substrate after drying.

5.4. *Industrial method of pectin film production*

Edible films are typically formed through solvent casting (wet process) or extrusion (dry process) (Suhag et al., 2020). Casting (a wet technique) is typically employed for bench and pilot-scale processes, while extrusion (dry) is a commercial-scale process that is widely used in food packaging manufacturing industries (Suhag et al., 2020). However, there are very few studies to date on the extrusion process of pectin's and blends to form films (de Oliveira Begali et al., 2021). One of the more attractive production methods of biopolymer film casting is continuous casting (Fig. 7). Film forming solutions are cast onto a conveyor belt that is fed into a drying chamber. Here, the solvent is evaporated off and reclaimed. The solution phase inverts on the belt and is subsequently removed. This allows for wet film techniques to be used on an industrial scale, while gaining several benefits over extrusion such as; accessibility to a variety of solvents, quicker casting, and faster drying times. This method can produce a continuous film, unlike most lab-scale casting techniques (Cai et al., 2020).

Pectin is well situated currently to take advantage of such manufacturing techniques. It has an established, safe history of use in the food industry. Greener methods are emerging thereby allowing for processing techniques transferable to textile manufacturing (such as forming gels and films). These films have a well understood chemistry. In biopolymer film production, it is unlikely that the chosen biopolymer used will possess all the necessary qualities to produce a well-rounded product, and that will satisfy all the technical and aesthetic packaging requirements. Films produced from neat pectin are hydrophilic and brittle, and employed alone, are unsuitable as a food packaging system (Nešić et al., 2017). At room temperature, pectin films are glassy in nature. Therefore, after solvent evaporation, cracks or curling of the film may occur (Šešlija et al., 2018). To prevent the formation of films with poor thermal, mechanical, and moisture barrier properties, pectin is usually blended with other compounds to modify its characteristics. Previously described crosslinking agents (Fig. 5) may be used during/after film formation to improve the mechanical properties of pectin based technologies. Like most biopolymer-based materials, pectin materials are typically mechanically inferior to petrochemically derived plastics. To address pectin's poor mechanical properties, pectin based materials may be crosslinked during/after production using previously described methods.

6. Pectin films properties

Being aware of the film forming components used in a blend, and the different properties each possess is vital in order to create a homogenous and visually attractive film that retains all the attributes required for food packaging, such as; low water vapor permeability, high tensile strength and so on. Pectin may be blended with; plasticizers; crosslinking agents; or other (bio)polymers which possess qualities pectin does not have (Gao et al., 2019). Pectin films, when used both alone in pure form or in blends produce very different materials characteristically, physically and behaviourally (Table 1). While pectin possesses numerous beneficial properties when it comes to film manufacture, it also has some limitations such as its high hydrophilicity. To overcome this particular problem, pectin is often incorporated into a composite or blend so as to obtain the necessary properties which it lacks. Pectin offers a strong, rigid, yet highly permeable and brittle film. Addition of plasticisers like glycerol or alternative polymers such as pullulan help overcome such limitations.

Plasticizers achieve this by lessening the interactions that take place between polymers within the film. From this addition, more flexible, processable films are formed (Suhag et al., 2020). By definition, a plasticizer is "a substantially non-volatile, high boiling, non-separating substance, which when added to another material, changes the physical and/or mechanical properties of that material". Several plasticizers (namely sorbitol, glycerol, and water) are used. These substances increase the interpolymer spacing and reduce internal hydrogen bonding (Maftoonazad et al., 2007). The use of plasticizers, like polyols, is a common method of improving barrier and mechanical properties in conventional plastic films (Gouveia et al., 2019).

It is worth mentioning that while the use of plasticizers is a common method of pectin films obtaining additional properties that pure pectin films lack, other functional ingredients can be added to the film forming solution to overcome various limitations or challenges also. Wang et al.,

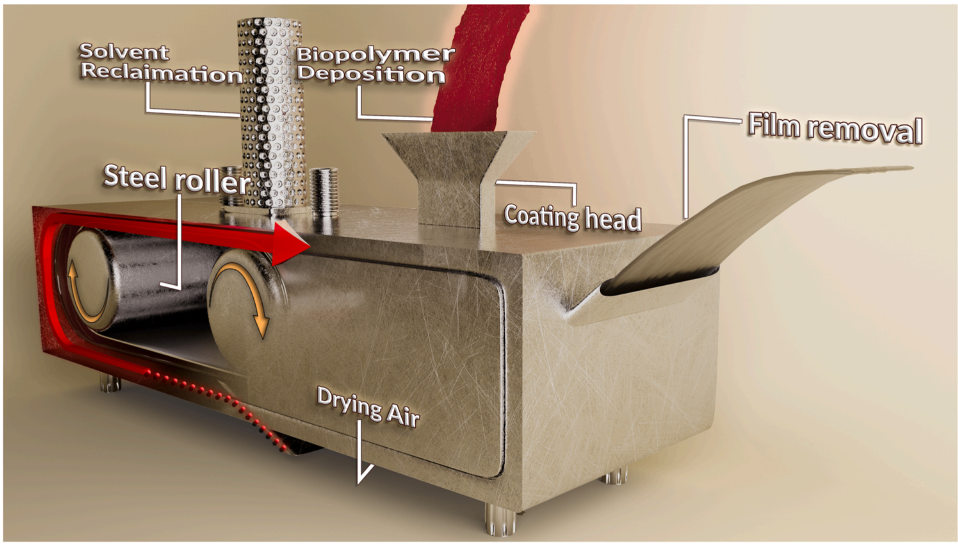


Fig. 7. Continuous film casting method.

Table 1
Pure pectin and pectin blend film properties.

Film's composition	pH	T,^{0}C of the solutions	RH at drying %	Film's properties					
				Thickness, mm	WVP, unit	Solubility in water, %	Moisture Content, %	Transparency	Elongation, %
Pectin 5% (w/v) solution (Mehraj & Sistla, 2022)	3	48	40–50	0.18	1.16^{-9} (g/m s Pa)	65 – 75	2–7	Low	N/A
5% (w/v) pectin, 30% w/v glycerol (Sood & Saini, 2022)	N/A	40	N/A	0.131	1.02 (g/Pa.h.m) × 10^{-12}	72.5	25.94	Low	7.15
Pectin/glycerol (P:G = 5.00:1.26 w/w) (Mehraj & Sistla, 2022)	3	48	40–50	0.212	$1.85E^{-9}$ (g/m s Pa)	100	2–7	Low	N/A
LMP (1% w/v), Glycerol (50% w/w), Calcium Chloride (20 mg/g pectin), (Brion-Espinoza et al., 2021)	3.81	35	50	0.0686	8.02 g/(m·s·Pa) × 10^{-9}	90.85	13.8 g water/g dry matter content	Transparent	N/A
LMP 1% (w/v), glycerol (50% w/w), $CaCl_2$ (680 μg/mL) Peptides from pepsin hydrolysis (Brion-Espinoza et al., 2021)	3.23	35	50	0.0491	9.43 g/(m·s·Pa) × 10^{-9}	86.63	9.75 g water/g dry matter content	Faint brown colour	N/A
Pectin/Pullulan (50:50 w/w) (Priyadarshi et al., 2021)	N/A	50	50	0.0571	1.22 × 10^{-9} g. m/m^2. Pa.s	N/A	N/A	Transparency increased with decreasing pectin content	3.1
Pectin/agar/Zinc Sulphide nano petals (ZnSNP 2.0 wt% based on polymers) (Roy & Rhim, 2021)	N/A	95	50	0.0656	0.54 × 10^{-9} g. m/m^2. Pa.s	N/A	N/A	High	9.9

2022 (Q. Wang et al., 2022), conducted an up-to-date review of some of the active ingredients that may be added to biodegradable packaging systems and how these ingredients can be released from the film matrix in a controlled manner. Antioxidants, nutrients, antimicrobials, and enzymes are examples of active ingredients that have commonly been used in food packaging to gain extra functionality and increase shelf-life of foodstuffs.

Blending biopolymers, such as chitosan for example, can improve water vapour permeability (WVP) and tensile strength when added to pectin for film manufacturing. Cast films employing the ratio of pectin: chitosan of 1:1 and 1:2 showed improved WVP properties, which is crucial for use in food packaging films. A blend ratio of 2:1 pectin:chitosan produced films with the highest tensile strength (6.49 MPa), compared to neat pectin and chitosan films which possessed tensile strength values of 1.22 MPa and 3.63 MPa, respectively. The optimal blending ratio of these two polymers was determined to be 1:1. This was attributed to favourable electrostatic interactions occurring between pectin and chitosan chains (Younis & Zhao, 2019). Pectin from waste AP may also be blended with miscible polymers [e.g., polyvinylpyrrolidone (PVP)] to improve film properties (Nešić et al., 2017). By incorporating 60 wt% PVP, pectin film, WVP is lowered by 58%, while producing films exhibiting far superior tensile strengths, 130% higher (16.7 MPa) than plasticized pectin films (7.2 MPa). Films blended with PVP were also thermally stable to 200 °C.

6.1. *Water vapor permeability (WVP) of pectin-based films*

Strong interactions between water vapor and pectin resulting from hydrogen bonding, and large differences in chemical potential at the air-biopolymer interface, drive the movement of water from zones of high-water vapour concentration to regions of low concentration (Bertuzzi et al., 2007). When the driving force is high [at a high relative humidity (RH) (64.9–92.0%)] WVP is greater. At low RH values (22.5–64.9%), there is a decrease in WVP. At low ambient RH, biopolymeric films contain less water, thereby lowering any plasticizing effect. At high RH, more water is absorbed and this “loosens” (plasticizes) the polymer matrix, increasing interpolymeric spacing, further allowing even more water to permeate the film, which in turn continues to plasticize the film (Alves et al., 2011).

Due to pectin's hydrophilicity, storage of pectin-based films at high humidity can result in the adsorption of water molecules, compromising the film's barrier properties. An effective way of combatting this problem is blending pectin films with hydrophobic compounds or cross-linking agents. SiO_2 nanoparticles have significantly reduced WVP values when blended with pectin (30–60% reduction). When compared against controls, the WVP of orange-derived pectin films incorporated with SiO_2 nanoparticles decreased by 14–80%. WVP values for mango fruit pectin films was reduced by 6–40%, following the incorporation of silicon nanoparticles (Spatafora Salazar et al., 2019). Notably, both sources of pectin produced films with WVP that was reduced by different amounts using SiO_2 particles.

As described earlier in this review, pectin's structure is composed of different domains, often characterised as ‘hairy’ and ‘smooth’ regions **(Figure 2)**. Given how the branched nature of different pectic substances influences the barrier properties of films, the extraction and purification of the ‘hairy’ regions is favourable. These pectin domains offer a more cohesive and compact network, which will work against WVP.

6.2. *Mechanical properties of pectin-based films*

As pectin confers high mechanical and adhesion properties in plant cell walls, it is not surprising that it has considerable potential to be the main component of a packaging film forming solution (Sood & Saini, 2022). Typically, mechanical properties are associated with a film's tensile strength and elongation at break ($\varepsilon = (\Delta L/L) \times 100$, measured in percentage). Both properties are largely influenced by the density of inter-molecular networks (i.e., changing pectin's distribution within the biopolymer network). Lower tensile strength and greater elongation at break values are usually associated with films constructed of pure pectin. These films are brittle in nature and can easily be destroyed at any point from production to storage, certainly unsuitable for packaging applications. This is typical of most polysaccharides, as without the addition of a plasticiser, they are brittle (Matta & Bertola, 2020). Therefore, it is often necessary to incorporate other biopolymers, or plasticisers, into pectin films to create films with properties that neat pectin films do not possess (Huang et al., 2021). Plasticizers (usually small molecules) can be used to modify three-dimensional structures of polymers by; **1)** increasing chain mobility and; **2)** reducing attractive intermolecular forces (Matta & Bertola, 2020).

In pure pectin films, increasing the pectin concentration from 1.5% to 3.5% increased tensile strength from 8.9 N to 21.6 N. This increase is attributable to a rise in pectin-pectin chain interactions, creating a compact network. When plasticizers such as glycerol are added to the formulation, the tensile force of the pectin film can decrease from 24.3 N to 14.8–15.1 N. This is largely believed to be due to the decrease in the number of intermolecular cross-links between pectin chains (Galus & Uchański, & Lenart, 2013).

Crosslinking (reduction of interchain distance by forming bonds between polymer chains, **(**Fig. 5**)** of LMP can be achieved using divalent cations (Ca^{2+}). Unmodified, pectin produces films with high water solubility (63.66%), high water permeability (0.15 g m/m^2 sec Pa), and low tensile strength (153 KPa). Crosslinking with $CaCl^2$ improved pectin film water solubility (59.82%), WVP (0.13 ng m/m^2 sec Pa), and tensile strength (193 KPa) (Kang et al., 2005). Polymer blending is used to produce a film product with physical, chemical, and biological properties greater than the sum of its parts (Younis & Zhao, 2019).

When the tensile force is decreased on addition of plasticizer, the elongation at break values increases. This essentially means that the film has become more flexible and elastic and that the force that is required to break the film decreases. It has been demonstrated that films that are made solely of polymeric substances, with the absence of a plasticizer, tend to be brittle in nature (Galus & Uchański, & Lenart, 2013); (Bayarri et al., 2014); (Hassan et al., 2021); (Ciriminna et al., 2020); (Minzanova et al., 2018); (Ciriminna et al., 2020); (Hassan et al., 2021); (Espitia, Du, et al., 2014); (Cai et al., 2020); (Jovanović et al., 2021); (Hassan et al., 2021).

7. Conclusion

Current manufacturing methods cannot continue indefinitely. With governmental and societal pressure increasing, the food industry is actively moving in a more sustainable direction. Food products are currently packaged in materials which take hundreds of years to degrade, due to the intrinsic chemical inertness of such materials. The precursors to form these materials take millennia to form naturally. Continued reliance on a finite feedstock of oil will fail to meet the increased demand for food packaging resulting from a growing population.

As food items spoil in a fraction of the time it takes the packaging to degrade. Next generation packaging must be designed with an appropriate lifetime in mind, yet capable of preventing food waste and spoilage within a realistic commercial timeframe. Packaging produced using the circular economy model is the only means of preventing plastic waste accumulation, while reintroducing valuable materials into the flow of commerce.

Pectin is a non-toxic, biodegradable, and biocompatible polymer that displays great potential to be incorporated into sustainable food packaging systems. AP derived pectin is underutilised within the food industry, with AP largely and inconsistently allocated as animal feed. Films produced solely from pectin or polysaccharides are limited in application, due to their weak water vapour barrier properties and brittle nature. However, both blending and compositing pectin is an effective strategy at utilizing existing fruit-derived waste streams for future industrial applications, such as 'green plastics' manufacture.

Despite pectin's potential use in this industry, at the time of writing and having extensively reviewed the scientific literature, there are no studies or products that deal with the preservation of food products using pectin films or pectin based coatings. Many studies outlined in this paper investigate the development of pectin films. However, for packaging products of this nature to be produced in the future, extensive research is required to be carried out on the shelf-life of food products that are utilising this form of packaging. Only then will the true potential and benefits of constructing biodegradable packaging from pectin, and indeed other biopolymer sources, be truly realised.

The food industry has laid the foundation for most transferable knowledge (to the polymer sector) regarding the processing of pectin in the formation of many confectionary products. Pectin is poised to take advantage of current industrial-scale manufacturing techniques (Fig. 7). Knowledge obtained by the food industry regarding the processing of pectin puts it ahead of other biopolymers currently under investigation. All this indicates that while pectin has yet to mature into a viable commercial material, it has a very promising future.

CRediT authorship contribution statement

Ian Butler: Writing, Methodology, Investigation. **Russell Banta**: Supervision, Data curation, Visualization, Resources, Project administration, Writing – review & editing. **Shivani Pathania**: Funding acquisition. **Joe Kerry**: Supervision, Project administration, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

Acknowledgements

This research received funds from the Food Institutional Research Measure (FIRM), grant number 2019R428, administered by the Department of Agriculture, Food and the Marine.

References

Alves, V. D., Castelló, R., Ferreira, A. R., Costa, N., Fonseca, I. M., & Coelhoso, I. M. (2011). Barrier properties of carrageenan/pectin biodegradable composite films. *Procedia Food Science, 1*, 240–245. https://doi.org/10.1016/j.profoo.2011.09.038

Arshadi, M., Attard, T. M., Lukasik, R. M., Brncic, M., da Costa Lopes, A. M., Finell, M., Geladi, P., Gerschenson, L. N., Gogus, F., Herrero, M., Hunt, A. J., Ibáñez, E., Kamm, B., Mateos-Aparicio, I., Matias, A., Mavroudis, N. E., Montoneri, E., Morais, A. R. C., Nilsson, C., … Yuste-Córdoba, F. J. (2016). Pre-treatment and extraction techniques for recovery of added value compounds from wastes throughout the agri-food chain (Royal Society of Chemistry) *Greening Chemistry* (Vol. 18,(Issue 23), 6160–6204. https://doi.org/10.1039/c6gc01389a.

Baiano, A. (2014). Recovery of biomolecules from food wastes - A review (MDPI AG) *In Molecules* (Vol. 19,(Issue 9), 14821–14842. https://doi.org/10.3390/molecules190914821.

Barreira, J. C. M., Arraibi, A. A., & Ferreira, I. C. F. R. (2019). Bioactive and functional compounds in apple pomace from juice and cider manufacturing: Potential use in dermal formulations. In *Trends in Food Science and Technology* (Vol. 90, pp. 76–87). Elsevier Ltd,. https://doi.org/10.1016/j.tifs.2019.05.014

Basanta, M. F., Ponce, N. M. A., Rojas, A. M., & Stortz, C. A. (2012). Effect of extraction time and temperature on the characteristics of loosely bound pectins from Japanese plum. *Carbohydrate Polymers, 89*(1), 230–235. https://doi.org/10.1016/j.carbpol.2012.03.001

Beikzadeh, S., Khezerlou, A., Jafari, S. M., Pilevar, Z., & Mortazavian, A. M. (2020). Seed mucilages as the functional ingredients for biodegradable films and edible coatings in the food industry. In *Advances in Colloid and Interface Science* (Vol. 280). Elsevier B.V.. https://doi.org/10.1016/j.cis.2020.102164

Bertuzzi, M. A., Castro Vidaurre, E. F., Armada, M., & Gottifredi, J. C. (2007). Water vapor permeability of edible starch based films. *Journal of Food Engineering, 80*(3), 972–978. https://doi.org/10.1016/j.jfoodeng.2006.07.016

Boiteau, J. M., & Pingali, P. (2023). Can we agree on a food loss and waste definition? An assessment of definitional elements for a globally applicable framework. *Global Food Security, 37*, Article 100677. https://doi.org/10.1016/j.gfs.2023.100677

Brion-Espinoza, I. A., Iñiguez-Moreno, M., Ragazzo-Sánchez, J. A., Barros-Castillo, J. C., Calderón-Chiu, C., & Calderón-Santoyo, M. (2021). Edible pectin film added with peptides from jackfruit leaves obtained by high-hydrostatic pressure and pepsin hydrolysis. *Food Chemistry: X, 12*. https://doi.org/10.1016/j.fochx.2021.100170

Cai, J., Xiao, J., Chen, X., & Liu, H. (2020). Essential oil loaded edible films prepared by continuous casting method: Effects of casting cycle and loading position on the release properties. *Food Packaging and Shelf Life, 26*. https://doi.org/10.1016/j.fpsl.2020.100555

Calvete-Torre, I., Muñoz-Almagro, N., Pacheco, M. T., Antón, M. J., Dapena, E., Ruiz, L., Margolles, A., Villamiel, M., & Moreno, F. J. (2021). Apple pomaces derived from mono-varietal Asturian ciders production are potential source of pectins with appealing functional properties. *Carbohydrate Polymers, 264*. https://doi.org/10.1016/j.carbpol.2021.117980

Cao, L., Lu, W., Mata, A., Nishinari, K., & Fang, Y. (2020). Egg-box model-based gelation of alginate and pectin: A review. In *In Carbohydrate Polymers* (Vol. 242). Elsevier Ltd,. https://doi.org/10.1016/j.carbpol.2020.116389

Carvalho, A. P. A. de, & Conte Junior, C. A. (2020). Green strategies for active food packagings: A systematic review on active properties of graphene-based nanomaterials and biodegradable polymers. In *Trends in food science and technology* (Vol. 103, pp. 130–143). Elsevier Ltd,. https://doi.org/10.1016/j.tifs.2020.07.012

Celus, M., Kyomugasho, C., van Loey, A. M., Grauwet, T., & Hendrickx, M. E. (2018). Influence of pectin structural properties on interactions with divalent cations and its associated functionalities. In *Comprehensive reviews in food science and food safety* (Vol. 17, pp. 1576–1594). Blackwell Publishing Inc,. https://doi.org/10.1111/1541-4337.12394

Chakravartula, S. S. N., Soccio, M., Lotti, N., Balestra, F., Dalla Rosa, M., & Siracusa, V. (2019). Characterization of composite edible films based on pectin/alginate/whey protein concentrate. *Materials, 12*(15). https://doi.org/10.3390/ma12152454

Chan, S. Y., & Choo, W. S. (2013). Effect of extraction conditions on the yield and chemical properties of pectin from cocoa husks. *Food Chemistry, 141*(4), 3752–3758. https://doi.org/10.1016/j.foodchem.2013.06.097

Chen, M., & Lahaye, M. (2021). Natural deep eutectic solvents pretreatment as an aid for pectin extraction from apple pomace. *Food Hydrocolloids, 115*. https://doi.org/10.1016/j.foodhyd.2021.106601

Chen, X., Xiao, J., Cai, J., & Liu, H. (2020). Phase separation behavior in zein-gelatin composite film and its modulation effects on retention and release of multiple bioactive compounds. *Food Hydrocolloids, 109*. https://doi.org/10.1016/j.foodhyd.2020.106105

Cheng, K., Hao, W., Wang, Y., Yi, P., Zhang, J., & Ji, W. (2020). Understanding the emission pattern and source contribution of hazardous air pollutants from open burning of municipal solid waste in China. *Environmental Pollution, 263*. https://doi.org/10.1016/j.envpol.2020.114417

Cho, E. H., Jung, H. T., Lee, B. H., Kim, H. S., Rhee, J. K., & Yoo, S. H. (2019). Green process development for apple-peel pectin production by organic acid extraction. *Carbohydrate Polymers, 204*, 97–103. https://doi.org/10.1016/j.carbpol.2018.09.086

Cui, J., Zhao, C., Feng, L., Han, Y., Du, H., Xiao, H., & Zheng, J. (2021). Pectins from fruits: Relationships between extraction methods, structural characteristics, and functional properties. In *In Trends in Food Science and Technology* (Vol. 110, pp. 39–54). Elsevier Ltd,. https://doi.org/10.1016/j.tifs.2021.01.077

Dash, K. K., Ali, N. A., Das, D., & Mohanta, D. (2019). Thorough evaluation of sweet potato starch and lemon-waste pectin based-edible films with nano-titania inclusions for food packaging applications. *International Journal of Biological Macromolecules, 139*, 449–458. https://doi.org/10.1016/j.ijbiomac.2019.07.193

de Oliveira Begali, D., Ferreira, L. F., de Oliveira, A. C. S., Borges, S. V., de Sena Neto, A. R., de Oliveira, C. R., Yoshida, M. I., & Sarantopoulos, C. I. G. L. (2021). Effect of the incorporation of lignin microparticles on the properties of the thermoplastic starch/pectin blend obtained by extrusion. *International Journal of Biological Macromolecules, 180*, 262–271. https://doi.org/10.1016/j.ijbiomac.2021.03.076

Dranca, F., Talón, E., Vargas, M., & Oroian, M. (2021). Microwave vs. conventional extraction of pectin from Malus domestica 'Fălticeni' pomace and its potential use in hydrocolloid-based films. *Food Hydrocolloids, 121*. https://doi.org/10.1016/j.foodhyd.2021.107026

Dranca, F., Vargas, M., & Oroian, M. (2020a). Physicochemical properties of pectin from Malus domestica 'Fălticeni' apple pomace as affected by non-conventional extraction techniques. *Food Hydrocolloids, 100*. https://doi.org/10.1016/j.foodhyd.2019.105383

Dranca, F., Vargas, M., & Oroian, M. (2020b). Physicochemical properties of pectin from Malus domestica 'Fălticeni' apple pomace as affected by non-conventional extraction techniques. *Food Hydrocolloids, 100*. https://doi.org/10.1016/j.foodhyd.2019.105383

Espitia, P. J. P., Avena-Bustillos, R. J., Du, W. X., Teófilo, R. F., Soares, N. F. F., & McHugh, T. H. (2014). Optimal antimicrobial formulation and physical-mechanical properties of edible films based on açaí and pectin for food preservation. *Food Packaging and Shelf Life, 2*(1), 38–49. https://doi.org/10.1016/j.fpsl.2014.06.002

Fraeye, I., Duvetter, T., Doungla, E., van Loey, A., & Hendrickx, M. (2010). Fine-tuning the properties of pectin-calcium gels by control of pectin fine structure, gel composition and environmental conditions. *Trends in Food Science and Technology* (Vol. 21,(Issue 5), 219–228. https://doi.org/10.1016/j.tifs.2010.02.001

Galus, S., & Lenart, A. (2013). Development and characterization of composite edible films based on sodium alginate and pectin. *Journal of Food Engineering, 115*(4), 459–465. https://doi.org/10.1016/j.jfoodeng.2012.03.006

Galus, S., Uchański, P., & Lenart, A. (2013). COLOUR, MECHANICAL PROPERTIES AND WATER VAPOUR PERMEABILITY OF PECTIN FILMS. In Acta Agrophysica (Vol. 20, Issue 3). http://www.acta-agrophysica.org/pdf-104865–35749?filename=Colour_%20mechanical.pdf.

Gao, H. X., He, Z., Sun, Q., He, Q., & Zeng, W. C. (2019). A functional polysaccharide film forming by pectin, chitosan, and tea polyphenols. *Carbohydrate Polymers, 215*, 1–7. https://doi.org/10.1016/j.carbpol.2019.03.029

Gouveia, T. I. A., Biernacki, K., Castro, M. C. R., Gonçalves, M. P., & Souza, H. K. S. (2019). A new approach to develop biodegradable films based on thermoplastic pectin. *Food Hydrocolloids, 97*. https://doi.org/10.1016/j.foodhyd.2019.105175

Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., & Purnell, P. (2018). An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. In *In Journal of Hazardous Materials* (Vol. 344, pp. 179–199). Elsevier B.V,. https://doi.org/10.1016/j.jhazmat.2017.10.014

Hoagland, P.D., & Parris, N. (1981). Chitosan/Pectin Laminated Films. https://doi.org/https://doi.org/10.1021/jf950162s.

Hosseini, S. S., Khodaiyan, F., & Yarmand, M. S. (2016). Aqueous extraction of pectin from sour orange peel and its preliminary physicochemical properties. *International Journal of Biological Macromolecules, 82*, 920–926. https://doi.org/10.1016/j.ijbiomac.2015.11.007

Huang, J., Hu, Z., Hu, L., Li, G., Yao, Q., & Hu, Y. (2021). Pectin-based active packaging: A critical review on preparation, physical properties and novel application in food preservation. *Trends in Food Science & Technology, 118*, 167–178. https://doi.org/10.1016/j.tifs.2021.09.026

Jeya Jeevahan, J., Chandrasekaran, M., Venkatesan, S. P., Sriram, V., Britto Joseph, G., Mageshwaran, G., & Durairaj, R. B. (2020). Scaling up difficulties and commercial aspects of edible films for food packaging: A review. In *In Trends in Food Science and Technology* (Vol. 100, pp. 210–222). Elsevier Ltd,. https://doi.org/10.1016/j.tifs.2020.04.014

Kang, H. J., Jo, C., Lee, N. Y., Kwon, J. H., & Byun, M. W. (2005). A combination of gamma irradiation and CaCl2 immersion for a pectin-based biodegradable film. *Carbohydrate Polymers, 60*(4), 547–551. https://doi.org/10.1016/j.carbpol.2005.02.016

Kijchavengkul, T., & Auras, R. (2008). Compostability of polymers. *Polymer International, 57*(6), 793–804. https://doi.org/10.1002/pi.2420

Koubala, B. B., Kansci, G., Mbome, L. I., Crépeau, M. J., Thibault, J. F., & Ralet, M. C. (2008). Effect of extraction conditions on some physicochemical characteristics of pectins from "Améliorée" and "Mango" mango peels. *Food Hydrocolloids, 22*(7), 1345–1351. https://doi.org/10.1016/j.foodhyd.2007.07.005

Lei, Y., Wu, H., Jiao, C., Jiang, Y., Liu, R., Xiao, D., Lu, J., Zhang, Z., Shen, G., & Li, S. (2019). Investigation of the structural and physical properties, antioxidant and antimicrobial activity of pectin-konjac glucomannan composite edible films incorporated with tea polyphenol. *Food Hydrocolloids, 94*, 128–135. https://doi.org/10.1016/j.foodhyd.2019.03.011

Lorén, N., & Hermansson, A.-M. (2000). Phase separation and gel formation in kinetically trapped gelatin/maltodextrin gels. *In International Journal of Biological Macromolecules* (Vol. 27). ⟨www.elsevier.com/locate/ijbiomac⟩.

Ma, S., Yu, S. J., Zheng, X. L., Wang, X. X., Bao, Q. D., & Guo, X. M. (2013). Extraction, characterization and spontaneous emulsifying properties of pectin from sugar beet pulp. *Carbohydrate Polymers, 98*(1), 750–753. https://doi.org/10.1016/j.carbpol.2013.06.042

Maftoonazad, N., Ramaswamy, H. S., & Marcotte, M. (2007). Evaluation of factors affecting barrier, mechanical and optical properties of pectin-based films using response surface methodology. *Journal of Food Process Engineering, 30*(5), 539–563. https://doi.org/10.1111/j.1745-4530.2007.00123.x

Mao, G., Wu, D., Wei, C., Tao, W., Ye, X., Linhardt, R. J., Orfila, C., & Chen, S. (2019). Reconsidering conventional and innovative methods for pectin extraction from fruit and vegetable waste: Targeting rhamnogalacturonan I. In *In Trends in Food Science and Technology* (Vol. 94, pp. 65–78). Elsevier Ltd,. https://doi.org/10.1016/j.tifs.2019.11.001

Marić, M., Grassino, A. N., Zhu, Z., Barba, F. J., Brnčić, M., & Rimac Brnčić, S. (2018). An overview of the traditional and innovative approaches for pectin extraction from plant food wastes and by-products: Ultrasound-, microwaves-, and enzyme-assisted extraction. In *In Trends in Food Science and Technology* (Vol. 76, pp. 28–37). Elsevier Ltd,. https://doi.org/10.1016/j.tifs.2018.03.022

Martau, G. A., Mihai, M., & Vodnar, D. C. (2019). The use of chitosan, alginate, and pectin in the biomedical and food sector-biocompatibility, bioadhesiveness, and biodegradability (MDPI AG) *In Polymers* (Vol. 11)(Issue 11). https://doi.org/10.3390/polym11111837.

Masson-Delmotte, V., Zhai, P., Chen, Y., Goldfarb, L., Gomis, M.I., Matthews, J.B.R., Berger, S., Huang, M., Yelekçi, O., Yu, R., Zhou, B., Lonnoy, E., Maycock, T.K., Waterfield, T., Leitzell, K., & Caud, N. (2021). Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Edited by. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf.

Matta, E., & Bertola, N. (2020). Development and characterization of high methoxyl pectin film by using isomalt as plasticizer. *Journal of Food Processing and Preservation, 44*(8). https://doi.org/10.1111/jfpp.14568

Mehraj, S., & Sistla, Y. S. (2022). Optimization of process conditions for the development of pectin and glycerol based edible films: Statistical design of experiments. *Electronic Journal of Biotechnology, 55*, 27–39. https://doi.org/10.1016/j.ejbt.2021.11.004

Mohnen, D. (2008). Pectin structure and biosynthesis. *Current Opinion in Plant Biology* (Vol. 11,(Issue 3), 266–277. https://doi.org/10.1016/j.pbi.2008.03.006

Morales-Contreras, B. E., Wicker, L., Rosas-Flores, W., Contreras-Esquivel, J. C., Gallegos-Infante, J. A., Reyes-Jaquez, D., & Morales-Castro, J. (2020). Apple pomace from variety "Blanca de Asturias" as sustainable source of pectin: Composition, rheological, and thermal properties. *LWT, 117*. https://doi.org/10.1016/j.lwt.2019.108641

Mu, T., Sun, H., Zhang, M., & Wang, C. (2017). Sweet Potato Pectin. *In Sweet Potato Processing Technology* (pp. 183–261). Elsevier,. https://doi.org/10.1016/b978-0-12-812871-8.00004-0

Munarin, F., Tanzi, M. C., & Petrini, P. (2012). Advances in biomedical applications of pectin gels. *In International Journal of Biological Macromolecules* (Vol. 51,(Issue 4), 681–689. https://doi.org/10.1016/j.ijbiomac.2012.07.002

Nešić, A., Ružić, J., Gordić, M., Ostojić, S., Micić, D., & Onjia, A. (2017). Pectin-polyvinylpyrrolidone films: A sustainable approach to the development of biobased packaging materials. *Composites Part B: Engineering, 110*, 56–61. https://doi.org/10.1016/j.compositesb.2016.11.016

Pirsa, S. (2020). Biodegradable film based on pectin/Nano-clay/methylene blue: Structural and physical properties and sensing ability for measurement of vitamin C. *International Journal of Biological Macromolecules, 163*, 666–675. https://doi.org/10.1016/j.ijbiomac.2020.07.041

Priyadarshi, R., Kim, S. M., & Rhim, J. W. (2021). Pectin/pullulan blend films for food packaging: Effect of blending ratio. *Food Chemistry, 347*. https://doi.org/10.1016/j.foodchem.2021.129022

Rajmohan, K. V. S., Ramya, C., Raja Viswanathan, M., & Varjani, S. (2019). Plastic pollutants: effective waste management for pollution control and abatement. In *In Current Opinion in Environmental Science and Health* (Vol. 12, pp. 72–84). Elsevier B. V,. https://doi.org/10.1016/j.coesh.2019.08.006

Reich, S., & Cohen, Y. (1981). Phase Separation of Polymer Blends in Thin Films. https://doi.org/https://doi.org/10.1002/pol.1981.180190809.

Reichembach, L. H., & Lúcia de Oliveira Petkowicz, C. (2021). Pectins from alternative sources and uses beyond sweets and jellies: An overview. In *In Food Hydrocolloids* (Vol. 118). Elsevier B.V,. https://doi.org/10.1016/j.foodhyd.2021.106824

Ren, W., Qiang, T., & Chen, L. (2022). Recyclable and biodegradable pectin-based film with high mechanical strength. *Food Hydrocolloids, 129*. https://doi.org/10.1016/j.foodhyd.2022.107643

Robertson. (2013). Food Packaging Principles and Practice, Third Edition. https://doi.org/https://doi.org/10.1201/b21347.

Round, A. N., Rigby, N. M., MacDougall, A. J., & Morris, V. J. (2010). A new view of pectin structure revealed by acid hydrolysis and atomic force microscopy. *Carbohydrate Research, 345*(4), 487–497. https://doi.org/10.1016/j.carres.2009.12.019

Roy, S., & Rhim, J. W. (2021). Preparation of pectin/agar-based functional films integrated with zinc sulfide nano petals for active packaging applications. *Colloids and Surfaces B: Biointerfaces, 207*. https://doi.org/10.1016/j.colsurfb.2021.111999

Sandarani, M. (2017). A Review: Different Extraction Techniques of Pectin. *Journal of Pharmacognosy & Natural Products, 03*(03). https://doi.org/10.4172/2472-0992.1000143

Santagata, R., Ripa, M., Genovese, A., & Ulgiati, S. (2021). Food waste recovery pathways: Challenges and opportunities for an emerging bio-based circular economy. A systematic review and an assessment. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2020.125490

Sason, G., & Nussinovitch, A. (2021). Hydrocolloids for edible films, coatings, and food packaging. *In Handbook of Hydrocolloids* (pp. 195–235). Elsevier,. https://doi.org/10.1016/b978-0-12-820104-6.00023-1

Seenuvasan, M., Malar, C. G., & Growther, L. (2021). Production of a biopolymer film from biological wastes and its statistical analysis. *Bioresource Technology Reports, 13*. https://doi.org/10.1016/j.biteb.2020.100610

Šešlija, S., Nešić, A., Ružić, J., Kalagasidis Krušić, M., Veličković, S., Avolio, R., Santagata, G., & Malinconico, M. (2018). Edible blend films of pectin and poly (ethylene glycol): Preparation and physico-chemical evaluation. *Food Hydrocolloids, 77*, 494–501. https://doi.org/10.1016/j.foodhyd.2017.10.027

Shafie, M. H., Yusof, R., Samsudin, D., & Gan, C. Y. (2020). Averrhoa bilimbi pectin-based edible films: Effects of the linearity and branching of the pectin on the physicochemical, mechanical, and barrier properties of the films. *International Journal of Biological Macromolecules, 163*, 1276–1282. https://doi.org/10.1016/j.ijbiomac.2020.07.109

Shalini, R., & Gupta, D. K. (2010). Utilization of pomace from apple processing industries: A review. *Journal of Food Science and Technology* (Vol. 47,(Issue 4), 365–371. https://doi.org/10.1007/s13197-010-0061-x

Shih, Y. T., & Zhao, Y. (2021). Development, characterization and validation of starch based biocomposite films reinforced by cellulose nanofiber as edible muffin liner. *Food Packaging and Shelf Life, 28*. https://doi.org/10.1016/j.fpsl.2021.100655

Shivamathi, C. S., Moorthy, I. G., Kumar, R. V., Soosai, M. R., Maran, J. P., Kumar, R. S., & Varalakshmi, P. (2019). Optimization of ultrasound assisted extraction of pectin from custard apple peel: Potential and new source. *Carbohydrate Polymers, 225*. https://doi.org/10.1016/j.carbpol.2019.115240

Sid, S., Mor, R. S., Kishore, A., & Sharanagat, V. S. (2021). Bio-sourced polymers as alternatives to conventional food packaging materials: A review. *Trends in Food Science & Technology, 115*, 87–104. https://doi.org/10.1016/j.tifs.2021.06.026

Song, J. H., Murphy, R. J., Narayan, R., & Davies, G. B. H. (2009). Biodegradable and compostable alternatives to conventional plastics. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1526), 2127–2139. https://doi.org/10.1098/rstb.2008.0289

Sood, A., & Saini, C. S. (2022). Red pomelo peel pectin based edible composite films: Effect of pectin incorporation on mechanical, structural, morphological and thermal properties of composite films. *Food Hydrocolloids, 123*, Article 107135. https://doi.org/10.1016/j.foodhyd.2021.107135

Spatafora Salazar, A. S., Sáenz Cavazos, P. A., Mújica Paz, H., & Valdez Fragoso, A. (2019). External factors and nanoparticles effect on water vapor permeability of pectin-based films. In *In Journal of Food Engineering* (Vol. 245, pp. 73–79). Elsevier Ltd,. https://doi.org/10.1016/j.jfoodeng.2018.09.002

Suhag, R., Kumar, N., Petkoska, A. T., & Upadhyay, A. (2020). Film formation and deposition methods of edible coating on food products: A review. In *In Food Research International* (Vol. 136). Elsevier Ltd,. https://doi.org/10.1016/j.foodres.2020.109582

Tokiwa, Y., Calabia, B., Ugwu, C., Aiba, S., Tokiwa, Y., Calabia, B. P., Ugwu, C. U., & Aiba, S. (2009). Biodegradability of Plastics. *International Journal of Molecular Sciences, 10*(9), 3722–3742. https://doi.org/10.3390/ijms10093722

Tyuftin, A. A., & Kerry, J. P. (2021). Gelatin films: Study review of barrier properties and implications for future studies employing biopolymer films. *Food Packaging and Shelf Life, 29*, Article 100688. https://doi.org/10.1016/j.fpsl.2021.100688

United Nations. (2014). Plastic waste causes $13 billion in annual damage to marine ecosystems, says UN agency | | UN News. https://news.un.org/en/story/2014/06/471492-plastic-waste-causes-13-billion-annual-damage-marine-ecosystems-says-un-agency.

United Nations. (2019). Growing at a slower pace, world population is expected to reach 9.7 billion in 2050 and could peak at nearly 11 billion around 2100 | UN DESA | United Nations Department of Economic and Social Affairs. https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html.

United Nations. (2021). Comprehensive assessment on marine litter and plastic pollution confirms need for urgent global action. https://www.unep.org/news-and-stories/press-release/comprehensive-assessment-marine-litter-and-plastic-pollution.

United Nations. (2022). Food Loss and Waste Reduction | United Nations. https://www.un.org/en/observances/end-food-waste-day.

Velaga, S. P., Nikjoo, D., & Vuddanda, P. R. (2018). Experimental Studies and Modeling of the Drying Kinetics of Multicomponent Polymer Films. *Aaps Pharmscitech, 19*(1), 425–435. https://doi.org/10.1208/s12249-017-0836-8

Vidović, S., Tepić Horecki, A., Vladić, J., Šumić, Z., Gavarić, A., & Vakula, A. (2020). Apple. *Valorization of Fruit Processing By-products* (pp. 17–42). Elsevier,. https://doi.org/10.1016/B978-0-12-817106-6.00002-2

Wang, L. Z., Liu, L., Holmes, J., Kerry, J. F., & Kerry, J. P. (2007). Assessment of film-forming potential and properties of protein and polysaccharide-based biopolymer films. *International Journal of Food Science and Technology, 42*(9), 1128–1138. https://doi.org/10.1111/j.1365-2621.2006.01440.x

Wang, Q., Chen, W., Zhu, W., McClements, D. J., Liu, X., & Liu, F. (2022). A review of multilayer and composite films and coatings for active biodegradable packaging (Nature Research) *npj Science of Food* (Vol. 6)(Issue 1). https://doi.org/10.1038/s41538-022-00132-8.

Willats, W. G. T., Mccartney, L., Mackie, W., & Knox, J. P. (2001). Pectin: cell biology and prospects for functional analysis. *Plant Molecular Biology* (Vol. 47).

Xue, L., Zhang, J., & Han, Y. (2012). Phase separation induced ordered patterns in thin polymer blend films. *Progress in Polymer Science (Oxford)* (Vol. 37,(Issue 4), 564–594. https://doi.org/10.1016/j.progpolymsci.2011.09.001

Younis, H. G. R., & Zhao, G. (2019). Physicochemical properties of the edible films from the blends of high methoxyl apple pectin and chitosan. *International Journal of Biological Macromolecules, 131*, 1057–1066. https://doi.org/10.1016/j.ijbiomac.2019.03.096

Zhang, W., Zhang, Y., Cao, J., & Jiang, W. (2021). Improving the performance of edible food packaging films by using nanocellulose as an additive. *International Journal of Biological Macromolecules*, 288–296. https://doi.org/10.1016/j.ijbiomac.2020.10.185