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Pectin: emerging plant-based component for 3D bioprinting – a mini-review

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Abstract. This mini-review focuses on the recent usage of pectin for 3D bioprinting in biomedical and food industry applications by highlighting the design and functional optimisation of bioinks. It discusses the structural features of pectin, effects of physicochemical factors influencing gelation, designing of pectin-based bioinks, and applications of pectin based bioinks across various fields. Furthermore, it investigates the recent advancements in this field by tuning the rheological properties by crosslinking and blending with other polymers which eventually improvise the printing and stability of the printed constructs. It also discusses, current limitations including reproducibility and strategy for standardised formulation along with future directions in this field.

Keywords: pectin, 3D bioprinting, bioink, extrusion

1. INTRODUCTION

1.1. 3D bioprinting

3D printing, or additive manufacturing, has emerged as a fabrication technology that enables customised structures through the precise deposition of materials in successive layers using computer-aided design with material added horizontally. Features such as unique customisation capability and the flexibility of 3D product design, reduced costs, and minimized material wastage make it a promising technology across various applications (Shahrubudin *et al.*, 2019). Depending on the application, materials like hydrogels, metals, polymers, thermoplastics, and ceramics are used for printing (Iftekar *et al.*, 2023). Recently, the use of biomaterials in 3D printing has attracted significant attention since the need to make this technology more environmentally friendly and due to the increasing interest in biomedical and food applications. The incorporation of biomaterials as bioink enhances the versatility of this technique. Growing interest in 3D bioprinting is evident from the rapid growth of the global market, which is estimated to reach around 6.7 billion USD by 2033, up from 3.1 billion in 2025, driven largely by growing demand for tissue engineering and regenerative medicine, which highlights the need for biomaterials. Currently, due to need of replacement of the fossil-based components, natural biomolecules are tried in 3D printing. By comparing with synthetic polymers such as polylactic acid (PLA), polyethyeleneglycol (PEG), and poly(ε- caprolactone) (PCL), which are extensively used in 3D bioprinting due to their printability and tuneable mechanical properties plant-derived materials are particularly promising because of their biocompatibility, biodegradability, bioactivity, and mechanical stability (Jovic *et al.*, 2019).

Biomaterial-based 3D printing is most often utilized in the process of the ink jet or extrusion. Material deposition in these methods is performed at a high shear rate (Jovic *et al.*,

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2019). In extrusion-based 3D printing, bioink formulations are typically hydrogels made of various biomaterials or living cells (Gungor-Ozkerim *et al.*, 2018). Typical critical steps for successful 3D bioprinting are: bioink formulation with optimal rheological properties, optimization of 3D printer settings, ensuring the stability of 3D printed objects, and evaluation of printed objects (Fig. 1). These stages affect the quality, precision, and structural integrity of the final objects. In extrusion-based 3D printing, where the bioink filament is continuously extruded through the nozzle, the printability merely depends on the rheological properties such as viscosity profile, shear thinning, yield stress, viscoelasticity and storage modulus of the bioink. The viscosity profile determines the flow of material within the nozzle; if the viscosity is low, it reduces the printing pressure and allows smooth flow, and high viscosity may prevent the collapse of the printed structure. Shear thinning decreases the viscosity under applied shear stress, enabling stable extrusion and uniform filament deposition. Yield stress is responsible for maintaining the structure after printing, and viscoelasticity represents the balance between viscous flow and elastic recovery. Storage modulus (G') and rapid recovery after extrusion corresponds to withstanding deformation and maintaining the geometry of the printed construct (Chimene *et al.*, 2016). An ideal bioink should exhibit shear-thinning behaviour, and high yield stress to maintain a post-printing shape (Fu *et al.*, 2021; Hossain *et al.*, 2023).

1.2. Key structural features of pectin

1.2.1. Pectin competitors in bioink design

It has been reported that there are several biomaterials that can be useful for 3D bioprinting like alginate, gelatin and chitosan. Gao *et al.* (2021) reported that biocompatibility, rapid ionic gelation and most importantly low cost making alginate as a perfect bioink for 3D bioprinting of tissue and organ analogue. Despite of these advantages its poor printability, limited cell proliferation ability and lack of intrinsic cell adhesive moieties limit its usage in biomedical researches. Yin *et al.* (2018) stated that properties like biocompatibility, excellent cell viability and tunable rheological properties making gelatine a perfect bioink. However, its thermoresponsive property and weak mechanical stability limit their usage in 3D bioprinting of complex constructs. Chitosan has been widely explored in 3D bioprinting mainly for biomedical applications (Hidaka *et al.*, 2021) because of its biocompatibility and antimicrobial properties. Although these advantages are significant its poor solubility and inconsistent behaviour restricts its usages.

Here comes the significance of pectin which is having properties like tunable rheological property, cell compatibility as well as fine mechanical properties compared with other biopolymers discussed.

1.2.2. Pectin structure-rheology relations

Pectin, a complex polysaccharide composed of galacturonic acid monomers and an important structural component of the plant cell wall (Pasarin *et al.*, 2023), plays a vital role in intracellular adhesion, mechanical resistance of the cell wall, which provide foundation for its use in biofabrication. Presence of hydroxyl group and carboxyl group in pectin contributes to its high water retention capacity, while the carboxyl group enables ionic crosslinking to form stable hydrogel networks with tuneable mechanical properties which are essential for cell encapsulation and tissue engineering applications.

Pectin consists of three major domains: homogalacturonan (HG), rhamnogalacturonan I (RG I), and rhamnogalacturonan II (RG II), as presented in Fig. 2 (Mohnen,

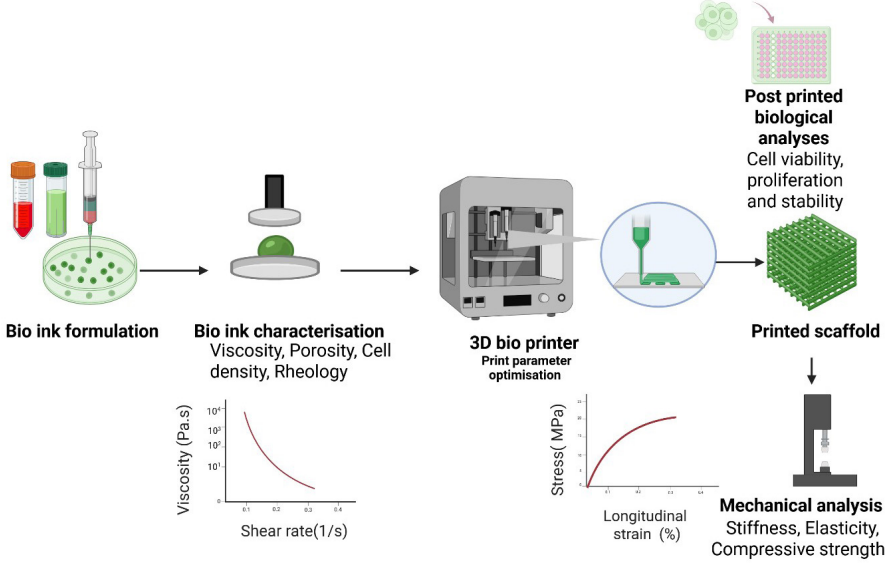


Fig. 1. A schematic workflow for bioink development, 3D bioprinting, and post-printing evaluation.

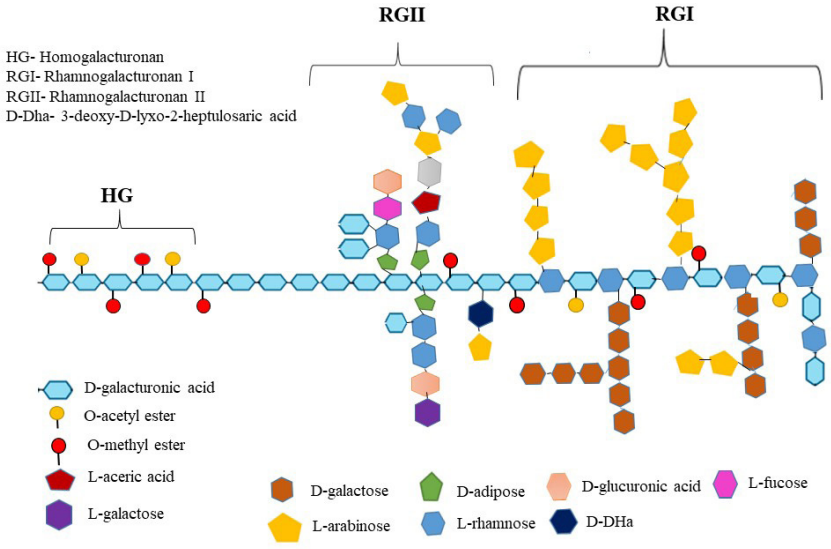


Fig. 2. Molecular structure of the pectin family, including major domains like homogalacturonan (HG), rhamnogalacturonan I (RG I), and rhamnogalacturonan II (RG II).

2008). HG is composed of a linear backbone of α-1,4-linked D-galacturonic acid residues in which some carboxyl groups are methyl esterified, acetylated, or both. HG plays a central role in pectin hydrogel formation by providing de-esterified uronic acid residues, which act as calcium binding sites. This Ca^{2+} mediated ionic coordination with adjacent HG chains leads to the formation of egg box model, which promotes the formation of 3D pectin network model responsible for gel formation. RG-I is composed of disaccharide units, each consisting of α-1,4-linked D-galacturonic acid and α-1,2-L-rhamnose, and the branched arabinan and galactan side chains are responsible for the hydrogel's flexibility and water retention capacity (Gawkowska *et al.*, 2018). In contrast, the structurally complex and highly branched RG-II consists of α-1,4-linked galacturonic acid residues, to which highly branched heteropolysaccharide side chains are attached (Fig. 2) (Yang *et al.*, 2022).The highly branched structure of RG-II enhances molecular interactions and network integrity, thereby contributing to the mechanical and rheological properties of the hydrogel. Beyond the primary structure of pectin, its secondary and higher-order structures are characterised by various intermolecular interactions, which are responsible for polymer assembly and hence influence the hydrogel formation. The abundant hydroxyl, carboxyl, and methyl ester functional groups in pectin chains enable multiple intermolecular interactions, including hydrogen bonds, ionic- crosslinking, calcium mediated interactions, hydrophobic interactions, and physical chain entanglement. These interactions facilitate network formation, pectin chain aggregation, and water retention within the hydrogel (Zdunek *et al.*, 2021). The presence of these functional groups also enables pectin to interact with various natural compounds like chitosan, proteins and starch through electrostatic interactions and hydrogen bonding (Gawkowska *et al.*, 2018).

Depending on the degree of methylation, pectin can be classified as high-methoxyl pectin (HMP) and low-methoxyl pectin (LMP). HMP has a degree of methylation greater than 50% while LMP has a degree of methylation less than 50% (Mierczyńska *et al.*, 2017). Degree of methylation influences both solubility and gel formation. LMP forms gels in the presence of calcium ions through the formation of the egg box model (Cao *et al.*, 2020), where polyuronate chains interact with calcium to form a stable network of gels. LMP forms gels in the presence of metallic ions in a wide range of pH, with or without the addition of sugars like sucrose (Kameshwar and Qin, 2018). HMP forms gels under lower pH (less than 3) (Bulone *et al.*, 2015) due to the hydrogen bond and hydrophobic interaction between pectin molecules. Increasing pectin concentration increases the strength of the gel formed (Gawkowska *et al.*, 2019). The rheological properties of pectin make it an effective thickening agent and stabilised rheology modifier (Lin *et al.*, 2021). Apart from the food industry, its applications are widespread across the health and pharmaceutical sectors, the industrial and environmental sectors, and food packaging. This is due to its antioxidant activity, metal-binding property, encapsulation capacity, and wound-healing abilities (Arumuganainar *et al.*, 2025). To enhance the applicability of pectin in various fields, its structure by different means, like enzymatic, alkali, and physical treatments, oxidations, and various methods of crosslinking, could be relatively easily tuned.

The pH, calcium ions, degree of esterification, concentrations of pectin, and temperature also significantly influence the thickness and density of the formed gels (Fig. 3)

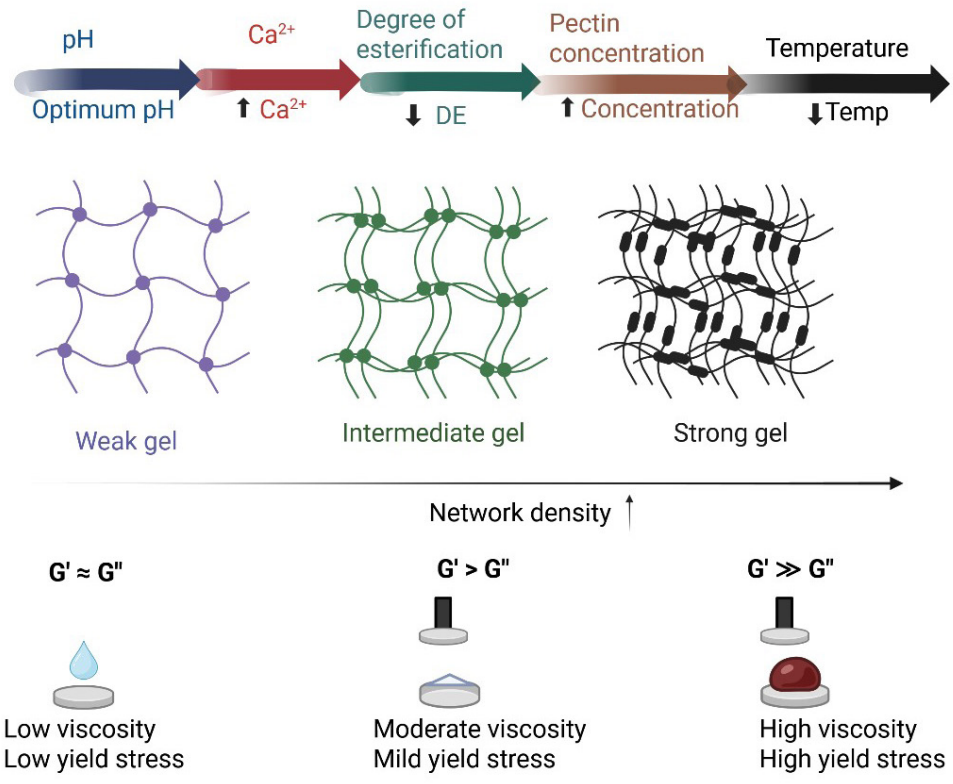


Fig. 3. Schematic overview of tuning of rheological properties of pectin using physicochemical parameters like pH, Ca^{2+}, degree of esterification, pectin concentration, temperature, and their influence on changes in viscosity and yield stress from weak to strong gel states.

(Cao and Li, 2018). Lootens *et al.* (2003) demonstrated that under acidic pH (below 3) pectin shows a denser network by reducing electrostatic repulsion between pectin chains. However, the effect of pH highly depends on calcium interaction and degree of amidation indicating that pH alone can't control the gel formation. The same study also reported that increased calcium ion concentration enhances the storage modulus and density of the gel network; however, these effects were dependent on maintaining an optimal calcium concentration. According to Ngouémazong *et al.* (2012) lower the degree of esterification provide more free carboxyl group which results in denser gel networks. The study further demonstrated that DE alone does not entirely determine the gel strength, as the distribution pattern of esterified group which significantly influences the gel homogeneity and network organisation. Amaral *et al.* (2022) find out that pectin concentration plays a vital role in gel strength and viscoelastic behaviour in Araca fruit pectin gels. The study showed that low pectin concentration produced, weak gel network with lower storage modulus (G'), mainly due to insufficient polymer chain interaction and limited calcium-mediated junction zones. It has been noted that increased pectin concentration leads to formation of gels with significantly higher elasticity and mechanical stability. Morris *et al.* (2010) reported that temperature has a significant effect on viscoelastic properties and density of pectin gels. Author's observed that increasing temperature leads to weekend gel by decreasing storage modulus and lower mechanical stability due to less intermolecular interaction and lower temperature favoured the formation of stronger gel with more stable elastic gels. While the study clearly highlights the thermosensitive nature of pectin, its limited structural characterisation restricted detailed interpretation of temperature induced network modifications.

Commercial pectin is extracted from commonly available and natural sources like citrus peel (Pasarin *et al.*, 2023) and apple pomaces (Rascón-Chu *et al.*, 2009), where it may occupy up to 60% of the cell wall, 0.5 to 4.0% of the total fresh weight of plants (Picot-Allain *et al.*, 2022). Unconventional sources of pectin contribute to a more sustainable approach by extracting it from industrial waste and bio products (Lara-Espinoza *et al.*, 2018). Therefore, this material is considered natural, functional, green-labelled, and with high potential to replace synthetic polymers in various composites (He *et al.*, 2021).

In short, the structural properties, tunable rheological properties, biocompatibility, abundance, crosslinking ability, and ease of modification make pectin a strong candidate for use as a functional component of bioinks for various applications. In this mini-review, we discuss the properties

of pectin used for 3D bioprinting and showcase biomedical and food applications. This summary of recently published results highlights the role of pectin in diverse bioink formulations and examines how it influences the rheological properties and accordingly the printability. Furthermore, this review summarises main challenges regarding 3D bioprinting using pectin as bioink that hamper its further application.

2. MAJOR FUNCTIONS OF PECTIN IN BIOINKS DESIGNING

Pectin has emerged as a versatile component of bioink formulations due to its tunable rheological properties, ability to form ionically cross-linked networks, compatibility with other polymers and nanomaterials, and potential to support biological functionality. Although pectin-only formulations often exhibit limited printability and insufficient mechanical stability, these limitations can be addressed through cross-linking and the development of composite or hybrid systems. Different pectin-based bioinks with formulation, composition, crosslinking method, and printing parameters are presented in Table 1.

2.1. Rheological enhancement

One of the key functions of pectin in bioink formulations is the modulation of rheological properties required for extrusion-based 3D printing. Pectin-based inks exhibit shear-thinning behaviour, in which viscosity decreases with increasing shear rate (Fig. 4a). This behaviour facilitates extrusion through the printing nozzle while allowing the material to recover its structure after deposition. The hysteresis observed during rheological measurements additionally indicates the thixotropic behaviour of pectin-based systems, reflecting time-dependent disruption and subsequent partial recovery of the polymer network.

The addition of pectin can effectively modify the rheological properties of multicomponent systems (Lapomarda *et al.*, 2021). For example, low-methoxylated pectin cross-linked with calcium chloride and supplemented with sugar syrup and BSA demonstrated tunable rheological behaviour suitable for extrusion-based printing (Vancauwenberghe *et al.*, 2017). Soluble solids increase intermolecular interactions and modifies both viscosity and viscoelasticity of the hydrogel. Changes in pectin concentration and $CaCl_2$ content can alter the extent of cross-linking and consequently affect viscosity, viscoelastic behaviour, printability, and the texture of printed constructs (Vancauwenberghe *et al.*, 2018b). Calcium-mediated crosslinking of pectin can be achieved through external gelation, where Ca^{2+} supplied from an external $CaCl_2$ solution induces rapid or near-instantaneous network formation during or after extrusion, facilitating filament stabilization and shape retention of 3D-printed constructs (Vancauwenberghe *et al.*, 2018a). In contrast, internal gelation using $CaCO_3$ enables a more gradual, pH-controlled release of Ca^{2+}, resulting in delayed crosslinking that provides better control over gelation kinetics and supports suitable extrusion, printability, and structural fidelity during 3D printing (Merli *et al.*, 2022). Pectin also plays an important rheological role in formulations containing cellulose-based nanomaterials. When combined with TEMPO-oxidised cellulose nanofibrils (TOCNF) that through physical entanglement and hydrogen bonding reinforces hydrogel network, pectin contributes to viscosity control, printability, and structural integrity (Cernencu *et al.*, 2019). Moreover, pectin improves the dispersion of TOCNF within the ink formulation, thereby facilitating extrusion and enhancing printability (Pitton *et al.*, 2021). Similarly, in composite hydrogels containing pectin and cellulose nanocrystals, $CaCl_2$-mediated pectin cross-linking enabled adjustment of rheological and structural properties, improving the reproducibility of printed constructs (Ma *et al.*, 2021). The rheological contribution of pectin is also evident in other composite systems. Kim *et al.* (2022) demonstrated that combining pectin with carboxymethyl cellulose (CMC) and ZnO nanoparticles improved rheological behaviour and extrusion characteristics compared with pectin-only formulations. The incorporation of CMC strengthened intermolecular interactions within the polymer network, thereby improving extrusion and post-deposition shape retention, while ZnO nanoparticles provided additional functionality.

2.2. Mechanical reinforcement

Despite its favourable rheological characteristics, pectin alone often provides insufficient mechanical stability for maintaining complex 3D architectures after printing. Mechanical reinforcement can be achieved through ionic cross-linking and the incorporation of complementary polymers or reinforcing nanomaterials.

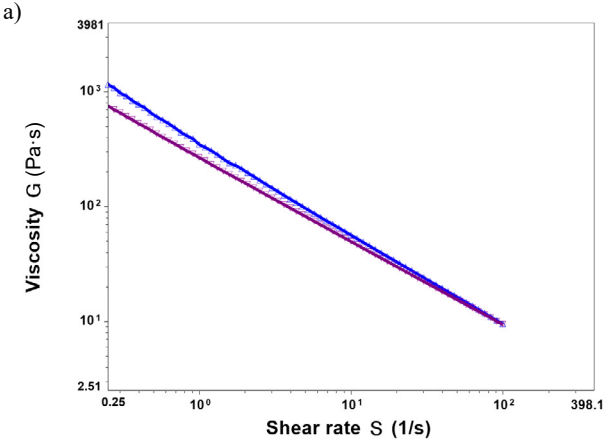
Low-methoxyl pectin readily undergoes calcium-mediated ionic cross-linking, resulting in the formation of a stable gel network commonly described by the “egg-box” model (Huang *et al.*, 2021). Calcium ions interact with negatively charged carboxyl groups along pectin chains, strengthening intermolecular associations and increasing the stability of the hydrogel network. Consequently, manipulation of pectin and $CaCl_2$ concentrations provides a means of controlling the degree of cross-linking, mechanical properties, texture, and structural integrity of printed constructs (Vancauwenberghe *et al.*, 2018b). Figure 4c demonstrates an example of grid structure produced from a low-methoxyl pectin bioink cross-linked with calcium chloride under optimised printing conditions. Mechanical performance can be further enhanced through the formation of hybrid hydrogels. In a gelatine-pectin system cross-linked with (3-glycidyloxypropyl)trimethoxysilane (GPTMS), the incorporation of pectin increased the stiffness of printed

Table 1. Different pectin-based bioinks with formulation, composition, crosslinking method, and printing parameters

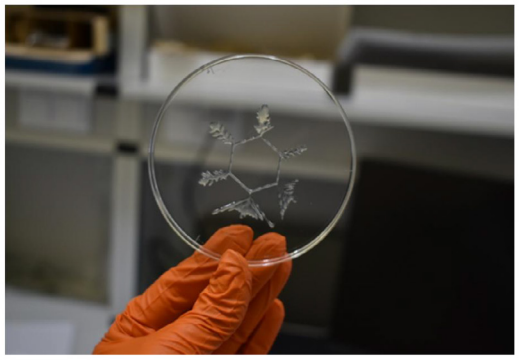
Formulation	Pectin type DM	Crosslinking method	Printing parameters Nozzle diameter	Application	References
Pectin+Sugar syrup+BSA	LMP	Ionic crosslinking by $CaCl_2$	Speed 5-15 mm s^{-1} Honeycomb structure Nozzle diameter 0.838 mm	Edible food printing	(Vancauwenberghe *et al.*, 2017)
Pectin+TOCNF	LMP	$CaCl_2$	Pressure 50-80 kPa Speed 20-35 mm Nozzle diameter 0.20 mm	Tissue engineering	(Cernencu *et al*., 2019)
Pectin+BSA	LMP	$CaCl_2$	Printing speed 10 mm s^{-1} Nozzle diameter 0.84 mm	Edible food printing	(Vancauwenberghe *et al.*, 2018a)
Pectin+Alginate +Pluronic	LMP	$CaCl_2$	Speed 4 mm s^{-1} Pressure 345 kPa Nozzle diameter 0.26 mm	Cell encapsulation	(Hu *et al*., 2021)
Pectin+$CaCl_2$	LMAP	$CaCl_2$	Speed 5 mm s^{-1} Pressure 50-60 kPa	No specific application	(Fiedot *et al*., 2025)
Pectin+$CaCO_3$+Collagen +NaCl+DMEM	LMP	$CaCO_3$	Speed 10-15 mm s^{-1} Pressure 4 kPa 0.41mm and 0.26 mm	Printing models of neural cells	(Merli *et al*., 2022)
Pectin+CMC+Glycerin+ ZnO+$CaCl_2$		$CaCl_2$	Speed 10 mm s^{-1} Pressure 150 kPa 0.26 mm	Fabricate functional films or scaffolds	(Kim *et al*., 2022)
Pectin+Gelatin	LMP	GPTMS	Speed 6-15 mm s^{-1} 0.84 mm to 0.26 mm	Tissue regeneration	(Lapomarda *et al*., 2021)
Pectin+TOCNF	LMP	$CaCl_2$	Speed 12-24 mm s^{-1} Pressure – not provided 0.84 mm, 0.60 mm, and 0.41 mm	Tissue engineering	(Pitton *et al*., 2021)
Pectin+Honey+Propolis extract+Chitosan,+β-cyclodextrin	HMP	Citric acid		Targeted oral delivery system for cannabidiol	(Andriotis *et al*, 2020a)
Pectin+CNC+Glycerol	HMP /LMP	$CaCl_2$ for LMP	Speed 25 mm s^{-1} Nozzle size 0.5 mm	Tissue engineering	(Ma *et al*., 2021)
Pectin+Honey+CBD, +β-cyclodextrin	HMP	Citric acid for lowering pH		Functional food products	(Andriotis *et al*., 2020b)
Pectin+Pea protein+Starch+Quinoa +flax seed oil Xanthan gum+CMC	HMP, Apple pectin, Citrus pectin	pH adjusted using HCl and NaOH	Speed 15 mm s^{-1} 0.84 mm	Edible food printing	(Gu *et al.*, 2024)
Pectin+Olive leaf extract+Glycerol+Sodium alginate	Not mentioned	$CaCl_2$	Speed 70 mm s^{-1} 1 mm	Wound healing	(Patitucci *et al.*, 2024)
Pectin+ Chitosan+ Lidocaine hydrochloride		Physical crosslinking	Speed 6 mm s^{-1} Pressure 74-104 kPa 0.25 mm	Wound healing	(Long *et al*., 2019)
Pectin +Watermelon rind+Sugar	HMP	Citric acid in presence of sugar	Speed 800 mm min^{-1} Pressure 1.5 bar Nozzle diameter 0.84 mm	Edible food printing	(Keerthy *et al*., 2025)
Potato starch + Pectin+Sugar+Citric acid	HMP	Citric acid in presence of sugar	Speed 5 mm s^{-1} Nozzle diameter 1 mm	Edible food printing	(Erandi *et al.*, 2023)

BSA – bovine serum albumin, LMP – low methoxyl pectin, TOCNF-TEMPO-oxidised cellulose nanofiber, DMEM – Dulbecco's modified Eagle's medium, CMC – carboxylmethyl cellulose, GPTMS – (3-glycidyloxypropyl) trimethoxysilane, HMP – high methoxyl pectin, CNC – cellulose nanocrystal, CBD – cannabidiol, LMAP – low methoxylated amidated pectin.

a)



b)



c)

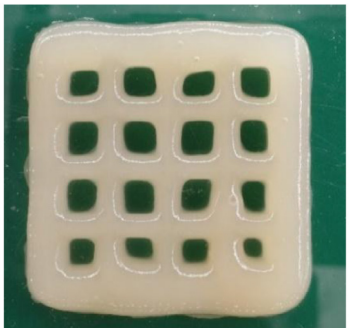


Fig. 4. a) Example of viscosity-shear rate relationship of the material, which shows shear thinning behaviour of pectin as the decrease in viscosity with increase in shear rate. The hysteresis loop indicates the thixotropic nature of about 4.41 wt% pectin cross-linked with 17 mM calcium chloride, and time-dependent structural breakdown and partial breakdown of pectin networks (own result). b) Example of 3D printed snowflake structure from the bioink made of 5 wt% pure pectin at a pressure of 20 kPa. c) 3D printed grid structure of 30×30×3 mm dimension with a pressure of 30 kPa and speed of 5 mm s^{-1}, made of pectin 4.41 wt% cross-linked with 24 mM calcium chloride bioink. Author's own data.

and lyophilised gelatine-pectin-GPTMS microsponges (Lapomarda *et al.*, 2021). Similarly, ultrasound treatment combined with pH adjustment enhanced the gel strength and elasticity of bioinks composed of apple or citrus pectin and pea protein, resulting in improved stability of the printed structures (Gu *et al.*, 2024). Polymer-polymer interactions can also reinforce pectin-based constructs. Long *et al.* (2019) developed a 3D-printed pectin-chitosan hydrogel for sustained delivery of lidocaine hydrochloride. Ionic interactions between pectin and chitosan promoted network formation and improved shape fidelity. A comparable reinforcement effect was reported for pectin-CMC-ZnO formulations, in which interactions between pectin and CMC enhanced structural fidelity and shape retention (Kim *et al.*, 2022). Nanocellulose provides another effective strategy for reinforcing pectin-based inks. In TOCNF-containing formulations, pectin contributes to the formation of a printable network with improved structural integrity (Cernencu *et al.*, 2019; Pitton *et al.*, 2021). Likewise, cellulose nanocrystals can reinforce pectin-based composite hydrogels, while calcium-mediated cross-linking of the pectin phase provides additional control over network strength and structural stability (Ma *et al.*, 2021). Thus, combining ionic cross-linking with polymeric or nanocellulose reinforcement represents an effective approach to overcoming the relatively weak mechanical stability of pectin-only inks.

2.3. Biological performance

In addition to controlling printability and mechanical stability, pectin-based formulations can provide an environment compatible with living cells. Experiments have demonstrated the potential of pectin-containing bioinks to support cytocompatibility and cell viability in 3D-bioprinted constructs.

Merli *et al.* (2022) developed a pectin-based bioink for 3D bioprinting of neural tissue models that demonstrated high printability, cytocompatibility, and reproducibility. In this system, pectin cross-linking through $CaCO_3$ was controlled by pH-dependent kinetics, eliminating the need for post-printing treatments or additional cross-linking steps. This approach provided sufficient structural stability while maintaining conditions compatible with biological components. High pectin content in TOCNF-based bioinks has also been associated with good prin-tability and cell viability of up to 80% (Pitton *et al.*, 2021), indicating that pectin-nanocellulose systems can simultaneously provide rheological support and a suitable cellular environment. Pectin-containing formulations have additionally demonstrated biological functionality in therapeutic applications. Hu *et al.* (2021) developed an alginate-pectin bioink as a strategy for β-cell immunoisolation. In this system, pectin contributed not only to structural integrity and printability but also to the immunomodulatory characteristics of the construct and protection of encapsulated β-cells. Another example is provided by alginate-pectin formulations containing olive extract for the fabrication of wound-healing films (Patitucci *et al.*, 2024). Polyphenols from olive extract provided antioxidant and anti-inflammatory activity, whereas $CaCl_2$-mediated cross-linking of the pectin-containing matrix was associated with enhanced fibroblast motility and increased collagen I

expression, potentially contributing to accelerated wound healing. Pectin can also assist in maintaining moisture within printable wound-healing formulations containing chitosan, cyclodextrin, and propolis (Andriotis *et al.*, 2020a).

2.4. Food applications

The rheological and structural functions of pectin are also particularly relevant to 3D food printing, where printable formulations must simultaneously exhibit appropriate extrusion behaviour, shape fidelity, texture, and stability after deposition.

The printability of low-methoxyl pectin in 3D food printing depends on several factors, including the botanical source and molecular structure of pectin as well as the type of sugar incorporated into the formulation, which can modulate the viscoelastic properties of the ink (Fiedot *et al.*, 2025). In particular, glucose-standardised low-methoxyl amidated pectin significantly influenced the quality and stability of printed constructs, demonstrating the importance of pectin-sugar interactions in designing printable food formulations. Pectin can also interact synergistically with food-derived proteins and polysaccharides. Gu *et al.* (2024) reported enhanced gel strength and elasticity in formulations composed of apple or citrus pectin and pea protein following ultrasound treatment combined with pH adjustment. These changes resulted in improved stability of the printed food structures. Similarly, Keerthy *et al.* (2025) demonstrated that pectin incorporation enhanced the rheological and extrusion characteristics of a watermelon-rind-based ink designed for 3D-printed gummy production. The optimised formulation exhibited improved texture and shape fidelity, suggesting that hydrocolloid additives such as pectin can overcome the poor printability frequently associated with fibre-rich food by-products. Erandi *et al.* (2023) further demonstrated synergistic interactions between pectin and potato starch. Compared with single-component systems, the composite formulation exhibited increased gel strength, improved textural stability over time, and better printability due to reinforcement of the viscoelastic network. These properties contributed to smoother extrusion and improved retention of the printed shape. Beyond conventional food structuring, pectin-containing printable formulations also show potential in nutraceutical applications. Andriotis *et al.* (2020b) developed a 3D-printable formulation containing cannabidiol/cyclodextrin inclusion complexes, demonstrating how functional additives can be incorporated into hydrocolloid-based printing systems while maintaining appropriate printability and stability. Such studies highlight the potential of pectin as a multifunctional hydrocolloid for the development of customised foods, functional products, and nutraceutical formulations.

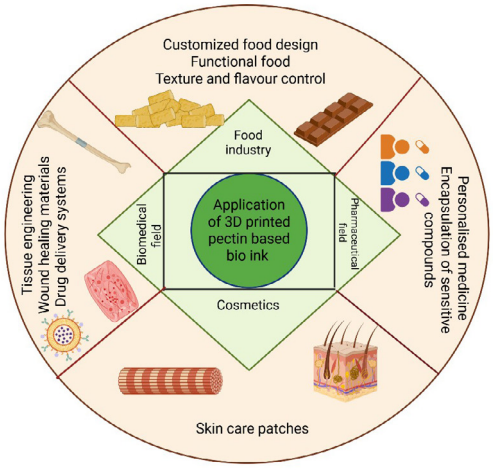


Fig. 5. Summary of successful applications of pectin-based 3D printing and bioprinting in the food, biomedical, cosmetic, and pharmaceutical industries.

3. APPLICATIONS OF 3D BIOPRINTING WITH PECTIN-BASED BIOINK

Three-dimensional printed constructs fabricated from pectin-containing bioinks have potential applications across biomedical, pharmaceutical, and food-related fields (Fig. 5). The naturally occurring polysaccharide structure of pectin enables the formation of hydrogels with favourable rheological properties, while its biocompatibility and biodegradability support its use in biologically active printing systems. However, pectin-only bioinks often exhibit insufficient mechanical strength and limited structural stability. Consequently, composite formulations, chemical modification, and tailored crosslinking strategies have been increasingly employed to improve structural performance while preserving the biological functionality of pectin-based systems.

3.1. Tissue engineering

Pectin has emerged as a promising component of 3D-printed scaffolds for tissue engineering because of its biocompatibility, biodegradability, and hydrogel-forming ability. These characteristics can provide a supportive microenvironment for cellular attachment, proliferation, and tissue regeneration. Nevertheless, the limited mechanical strength and stability of pectin-only bioinks have stimulated the development of multicomponent formulations in which pectin is combined with other polymers to achieve an appropriate balance between biological functionality and structural support.

Musculoskeletal tissue engineering, particularly cartilage regeneration, represents an important potential application of pectin-based 3D bioprinting because of the limited self-repair capacity of cartilage. Chang *et al.* (2023) developed a multicomponent bioink composed of potato-pulp-derived pectin RG-I, alginate, and gelatin for

musculoskeletal tissue regeneration. The formulation was designed to support chondrocyte incorporation and viability during 3D bioprinting. In this system, pectin contributed bioactive and anti-inflammatory properties, whereas gelatin and alginate provided structural integrity and biocompatibility. This approach illustrates how synergistic interactions between multiple polymers can overcome limitations associated with single-component bioinks.

The potential of pectin-containing composite systems for tissue engineering was also demonstrated by Michailidou *et al.* (2021), who developed a chitosan-pectin hydrogel and investigated the role of polymer interactions in controlling rheological behaviour and printability. Formation of polyelectrolyte complexes modulated the viscoelastic properties of the bioink, promoting shear-thinning behaviour and structural stability and ultimately enabling high-fidelity printing. Optimisation of pneumatic extrusion-based 3D printing conditions produced constructs exhibiting good biocompatibility toward fibroblasts seeded onto the scaffolds. Notably, fibroblast survival on non-gelated scaffolds suggested that the pectin-containing formulation provided not only favourable rheological and printing properties but also a supportive cellular microenvironment, further highlighting its potential for tissue engineering applications.

An alternative strategy was reported by Pereira *et al.* (2018), who investigated chemical modification of pectin rather than increasing the number of components in the bioink. In contrast to conventional fabrication techniques, 3D bioprinting enables more precise spatial organisation of different cell types and facilitates the reproducible fabrication of patient-specific scaffolds, providing an important advantage for the development of biomimetic dermal tissues. Methacrylate-modified pectin was used for the fabrication of such constructs and subjected to a dual-crosslinking process. Before printing, the material underwent ionic crosslinking with $CaCl_2$, followed by UV-induced photopolymerisation after printing. This dual-crosslinking strategy enhanced the mechanical and structural integrity of the printed constructs. The study therefore demonstrates that improved biofabrication performance does not necessarily require highly complex multicomponent formulations and can instead be achieved through rational functionalisation and controlled crosslinking of pectin.

3.2. Drug delivery systems

The hydrogel-forming ability and chemical versatility of pectin also make it attractive for the development of controlled drug delivery systems. In particular, the possibility of modifying pectin chemically and controlling its network structure provides opportunities to regulate the incorporation and release of therapeutic compounds.

Wang *et al.* (2023) developed an injectable hydrogel based on oxidised pectin and diacylhydrazine-adipate-functionalised pectin for controlled drug delivery. The resulting system demonstrated cytocompatibility and anti-cancer activity, illustrating the potential of chemically modified pectin networks as carriers for therapeutic agents. Such approaches are relevant to personalised medicine, where printable or injectable hydrogel systems could potentially enable spatially and temporally controlled delivery of active compounds.

Pectin-based matrices can also be used to incorporate compounds with limited aqueous solubility. Andriotis *et al.* (2020b) developed a food-grade, 3D-printable pectin formulation containing cannabidiol (CBD)-cyclodextrin inclusion complexes. Pectin served as the primary structuring material, whereas glycerol acted as a plasticiser to modulate viscosity and flexibility, enabling stable extrusion and shape retention under optimised conditions. Incorporation of cyclodextrin complexes improved the dispersibility of lipophilic CBD within the aqueous pectin matrix, demonstrating the potential of pectin-based printable systems as edible delivery platforms for functional or bioactive compounds.

3.3. Wound healing

Pectin-based bioinks have also been investigated for wound-healing applications, where moisture retention, biocompatibility, mechanical stability, and the ability to support cellular attachment and growth are particularly important. The hydrogel-forming and water-retaining properties of pectin make it suitable for the fabrication of personalised wound dressings that can maintain a moist environment while providing structural support.

Passamai *et al.* (2023) developed a biopolymeric ink composed of pectin, carboxymethylcellulose (CMC), and microcrystalline cellulose (MCC) for the fabrication of personalised wound dressings. Within this formulation, MCC functioned as a thickening component, while pectin and CMC contributed to water retention and gel formation. The resulting printed scaffolds exhibited suitable mechanical properties and good biocompatibility with L929 fibroblasts, supporting their potential application as skin-contacting wound-healing materials. The applicability of pectin to skin-related systems extends beyond conventional wound dressings. Its non-toxic nature, film-forming ability, moisture-retention capacity, and compatibility with hydrogel fabrication have also encouraged its investigation in skin patches and 3D-bioprinted skin models. These characteristics indicate that pectin can serve both as a structural component of printed dressings and as part of biologically compatible matrices designed to support tissue regeneration.

3.4. In vitro disease models

Beyond regenerative applications, pectin-based bioinks are increasingly being explored for the fabrication of biologically relevant *in vitro* disease models, particularly for cancer research and therapeutic screening. In these applications, the bioink must provide sufficient structural fidelity for reproducible model fabrication while simultaneously supporting homogeneous cell distribution and maintaining cellular viability.

Teixeira *et al.* (2024) developed a pectin-based nanocomposite bioink incorporating nanofibrillated cellulose (NFC) and lysozyme amyloid nanofibrils (LNFs) for the fabrication of A375 melanoma cell-laden constructs. Incorporation of these nanofibrillar components improved the rheological properties and printability of the pectin-based matrix, contributing to high shape fidelity and homogeneous cell distribution within the printed tumour constructs. Such characteristics are particularly important for reproducing aspects of the tumour microenvironment and improving the physiological relevance and reproducibility of in vitro cancer models used for therapeutic screening.

Pectin-containing bioinks may additionally provide opportunities for modelling inflammatory and immune-related cellular responses. Hu *et al.* (2021) developed a multicomponent bioink composed of pectin, Pluronic F127, and alginate for β-cell encapsulation and immunoprotection. Insulin-producing β-cells encapsulated within the 3D-printed alginate-pectin constructs demonstrated improved survival under inflammatory stress and a reduced inflammatory response. The system therefore extended the role of bioinks beyond structural cell encapsulation toward modulation of the surrounding immune microenvironment. Although the approach has potential relevance to therapeutic strategies for type 1 diabetes, challenges including restricted nutrient diffusion and fibrotic overgrowth remain important limitations. From an in vitro perspective, such systems also illustrate the potential of pectin-containing matrices for investigating cell-material interactions and cellular responses under inflammatory conditions.

3.5. Food bioprinting

Three-dimensional food printing is an emerging technology for the rapid production of customised food structures. In addition to creating visually tailored products, digital fabrication enables the adaptation of food composition to individual dietary requirements and preferences (Derossi *et al.*, 2024). Digital design, accurate process control, potential energy efficiency, and opportunities for sustainable production further contribute to the development of this technology (Zhu *et al.*, 2023). Pectin is particularly attractive for food printing because of its gelation and thickening properties, which contribute to appropriate extrusion behaviour and preservation of the structural integrity of printed products.

Recent studies have focused on improving printability and developing customised confectionery products using hydrocolloid-based systems. Pectin has received particular attention because of its gelling and thickening properties, thermal responsiveness, and compatibility with sugar-rich formulations. Huang *et al.* (2022) investigated the production of customised candies using hot-extrusion 3D printing. The authors demonstrated that temperature, extrusion rate, and material composition were major determinants of printing performance. Nozzle height and diameter, layer height, nozzle movement, and printing speed additionally influenced deformation of the printed structures. These findings demonstrate the close relationship between formulation characteristics and processing parameters in hot-extrusion food printing, although nutritional functionality, sensory quality, and long-term stability require further investigation.

Vancauwenberghe *et al.* (2018a) extended pectin-based food printing toward more complex and functional designs by developing edible plant-based materials with customised shapes using a coaxial extrusion printing system. The pectin-containing matrix was capable of maintaining cell viability and metabolic activity during processing, highlighting its potential for the incorporation of sensitive biological components. This approach could facilitate the development of customised and bioactive food structures with specific nutritional and functional properties, reflecting a broader transition from purely structural food printing toward multifunctional food systems.

The importance of formulation design was also demonstrated by Vancauwenberghe *et al.* (2017), who developed a food ink based on low-methoxylated pectin, calcium chloride, and bovine serum albumin for the fabrication of customised porous food simulants. Although low-methoxylated pectin does not require high sugar concentrations for gel formation, the addition of sugar improved printability by modifying the viscoelastic properties of the formulation. This finding demonstrates that additives can improve processing performance beyond the intrinsic gelation properties of pectin. Nevertheless, translation of these results beyond controlled experimental conditions and toward large-scale production remains a challenge.

Pectin-containing systems have also been investigated for the valorisation of plant-derived materials and agro-industrial by-products. Keerthy *et al.* (2025) demonstrated the use of watermelon rind in a pectin-containing formulation for 3D-printed gummy production. Pectin acted as a rheological modifier, compensating for insufficient gel formation and enabling the fabrication of customised products with improved shape accuracy. This strategy additionally demonstrates the potential of 3D food printing to contribute to the valorisation of agro-industrial waste within circular-economy approaches.

A similar functional role of pectin was demonstrated by Erandi *et al.* (2023) using potato starch as the principal plant-derived polymer. Pectin facilitated stable gel formation

and enabled the printed gummy structures to retain their customised geometries. Formulations containing higher pectin concentrations showed favourable printability even after 14 days of cold storage. Pectin also reduced starch retrogradation, which can otherwise increase the hardness and brittleness of starch-based printed structures, thereby contributing to improved textural and structural stability during storage.

Finally, pectin-based food printing can be combined with the delivery of functional ingredients. As discussed above, Andriotis *et al.* (2020b) incorporated CBD-cyclodextrin inclusion complexes into a food-grade pectin-based printable matrix. The system combined the structural role of pectin with improved dispersibility of a lipophilic bioactive compound, demonstrating how 3D food printing can integrate customised geometry with functional ingredient delivery.

4. CHALLENGES AND FUTURE PERSPECTIVES

Despite growing interest in pectin-based inks for 3D bioprinting, their translation from laboratory studies to reproducible biomedical, food, and industrial applications remains challenging. Major limitations include the intrinsic variability of pectin, complex rheological and mechanical behaviour, the trade-off between printability and biological performance, as well as unresolved issues related to sterilization, storage stability, scale-up, and regulatory requirements.

Commercial pectins vary considerably depending on botanical origin, extraction and purification procedures, molecular weight, degree of esterification, acetylation, and branching (Chan *et al*., 2017; Zdunek *et al.*, 2021). These characteristics influence hydration, viscosity, shear-thinning behaviour, gelation, and susceptibility to ionic crosslinking, ultimately affecting printability and mechanical performance. Consequently, similar pectin concentrations may produce substantially different printing behaviour, making comparison between studies difficult. Standardized characterization and reporting of pectin properties are therefore essential for reproducible bioink development.

Paste-like inks can exhibit nonlinear viscoelastic behaviour, resulting in irregular flow, structural breakdown, and deformation during printing (Bugday *et al.*, 2026). Moreover, pectin hydrogels often show lower mechanical strength, less control over gelation kinetics, sensitivity to pH and ionic environment, and variability through batches associated with the natural source (Rubio-Martin del Campo *et al.*, 2025). These limitations explain why pectin is frequently combined with other polymers, nanocellulose, nanoparticles, or complementary crosslinking systems. Although these strategies improve structural performance, they also increase formulation complexity and make it more difficult to distinguish the intrinsic contribution of pectin from synergistic effects of the composite system.

Increasing polymer concentration, viscosity, or crosslinking density generally improves filament fidelity and structural stability but simultaneously increases extrusion pressure and shear stress, potentially compromising cell viability and bioactivity (Bian *et al.*, 2020). Excessive crosslinking may additionally restrict water penetration, reduce useful swelling, oxygen, nutrient, and metabolite transport within the hydrogel (Azeem and KuShaari, 2026). Therefore, bioink optimization should aim to balance between printability and designed function. Rheological optimization, rapid but controllable crosslinking, flexible regulation of extrusion parameters, and improvements in printing hardware and software have been proposed to address these challenges (Qiu *et al.*, 2025).

Sterilization methods may alter pectin molecular weight, viscosity, gelation behaviour, and mechanical properties (Munarin *et al.*, 2013), and their effects should therefore be evaluated as an integral part of bioink development. Similarly, storage may lead to microbial contamination, polymer degradation, phase separation, changes in viscosity, and physical ageing of hydrogel formulations (Morris *et al.*, 2010). Such changes can directly influence extrusion behaviour and printing reproducibility, highlighting the need for validated sterilization procedures, storage conditions, and shelf-life specifications. Most reported pectin-based systems have been evaluated using small laboratory batches, whereas industrial production requires reproducible raw-material sourcing, batch-to-batch consistency, scalable mixing and processing, increased printing throughput, and robust quality control. Cost-effectiveness, scalability, regulatory requirements, and mechanical performance have already been identified as important barriers to broader biomedical implementation (Abraham *et al.*, 2025). Future studies should therefore incorporate manufacturing and techno-economic considerations alongside material and printing optimization. Depending on the intended product, development may require compliance with relevant FDA and EMA regulatory frameworks, ISO standards or good manufacturing practice (GMP) requirements. The natural variability of pectin further emphasizes the need for well-defined material specifications, traceable sourcing, purity and microbiological criteria, validated sterilization, and reproducible manufacturing.

Future research should consequently move from predominantly empirical formulation development toward predictive and standardized bioink design. Artificial intelligence and machine-learning approaches could help establish relationships between pectin structure, formulation composition, rheological properties, printing parameters, and biological outcomes, accelerating optimization of multivariable formulations (Altun *et al.*, 2025). Smart and stimuli-responsive pectin hydrogels could additionally support 4D bioprinting, while multi-material printing may enable spatial organization of materials with different mechanical and biological functions within a single construct (Ashammakhi *et al.*, 2018). Sustainability represents

another promising direction, particularly because pectin can be recovered from fruit and vegetable processing residues. Integration of waste-derived pectin with 3D bioprinting and other digitally controlled manufacturing technologies could contribute to agro-industrial biomass valorization and circular production (Saha *et al.*, 2025). However, sustainable sourcing must be accompanied by rigorous structural characterization to ensure that variability of waste-derived pectin does not further compromise printing reproducibility.

5. CONCLUSIONS

Pectin-only bioinks face challenges like poor printability and stability. To overcome these limitations, multicomponent bioinks are being developed by incorporating other biomaterials with pectin. Structural features of pectin molecules and solution properties that commonly affect gelling properties may be used to tune the desired shear-thinning properties of the bioink.

It is already well documented that the search for a perfect 3D bioprinting material, which is both biocompatible and safer for clinical practices, has led to the development of pectin-based bioinks with promising advancements in drug delivery, tissue regeneration and wound healing. As a natural biopolymer, pectin is highly biologically variable (source-dependent). On the other hand, pectin has been extensively studied owing to its role in plants and its compatibility with other biopolymers, particularly in rheological studies. These reasons have already led to substantial theoretical knowledge, and multiple strategies for tuning the rheological properties of pectin have been developed. This also presents an opportunity to increase the use of pectin in the design of bioinks for 3D printing. However, other than basic material selection future research should focus on crosslinking strategies, improved control over rheology as well as gelation kinetics in order to improve the performance of 3D printing. Emerging strategies like stimuli responsive hydrogels, rapid crosslinking systems are expected to pave the way better for improvised applications in this field. Furthermore, the future research should focus on the scalability, cost effectiveness as well as long term stability of printed constructs.

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