



REVIEW

From Nature to Innovation: Exploring the Functional Properties and Multifaceted Applications of Seed Mucilage

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ABSTRACT: The trends of consuming or using eco-friendly, biodegradable products due to the change in the lifestyle of the people have led to the exploration of new sources from plants or animals. Seed mucilage (SeM) is an underexplored component of plants that can be brought into play to deal with such problems. Mucilage, a viscous polysaccharide that can be obtained when seeds like chia, flax, garden cress, and tomato get hydrated and form a slimy, gel-like substance around the seed coat, can be utilized due to its unique characteristics. It has been used in developing many products such as bio-based films, plant-based dressing wounds with antibacterial effects, a medium for oral drug delivery, edible coatings, etc. Primarily composed of soluble fiber, it exhibits effects on human health, including blood glucose management, cholesterol, weight reduction, antioxidant (AOx), and antimicrobial activity. It offers a range of functional properties, including emulsification, stabilization, foam formation, fat replacement, encapsulating agent, flocculation, coagulation, and medium for drug release. These attributes make SeM a suitable component for applications in various sectors like food and pharmacy. Further study in this field may open more opportunities to address environmental problems and contribute to sustainability. This review explores aspects of SeM, emphasizing its functional properties and highlighting its current as well as potential applications across various sectors.

KEYWORDS: Polysaccharide; seed mucilage; antioxidant; drug delivery; edible coating; antimicrobial; emulsifier

1 Introduction

Mucilage is a lipophilic polysaccharide comprised of monosaccharides, uronic acids, glycoproteins, and different types of bioactive compounds. This plant-derived polysaccharide becomes an enticing choice for a shift towards sustainable and biodegradable polymers in various sectors, including food, pharmaceutical, and cosmetic industries, with applications such as emulsifier, gelling agent, fat-replacer, and thickener [1]. Given its strong film-forming ability, it has also been utilized to create bio-based films [2]. Polysaccharide-based films are regarded as superior amongst the emerging sustainable coating/packaging materials [3]. In addition, mucilage acts as an additive and an encapsulating agent, providing anti-inflammatory, anti-hypercholesterolemic, laxative, and antibacterial effects [4].

Mucopolysaccharides are obtained from living organisms, including plants, bacteria, fungi, and animals. Compared to the mucilage obtained from the green algae and phytoplankton, which is typically created under stress conditions, the ones sourced from plants are readily available and formed as an integral part



of the plant cells. They are considered to be safe, bio-based products, economical, and eco-friendly [5,6]. Mucilage generally consists of two major fractions of polysaccharides, specifically hemicellulose (made up mostly of arabinoxylans, AXY) and pectin (arising from rhamnogalacturonan I, RHG-I) [5,7]. Neutral sugars such as D-xylose, D-galactose, and L-arabinose are spotted. Additionally, glycosidic linkages bind uronic acid residues to methyl pentose, pentose, and galactose. Biologically active compounds, including steroids, alkaloids, tannins, and phenolic compounds, are also found. Depending on the plant species, the functional properties and chemical composition vary greatly. Besides, agronomic variations related to climate, soil, and hydration conditions have a significant impact on the chemical composition of the mucilage. The physiological and morphological characteristics of the plants and the extraction methods employed consequently affect the nutritional value and the yield of the mucilage [4,5,8].

The secretion or the production of mucilage from various parts of the plants, including roots, leaves, stems, and seeds, helps in withstanding any changes in the environmental conditions. Especially in the seeds, it acts as a protective layer and promotes germination, seed dispersal, and seed coat formation. The capacity to generate mucilage by the fruit pericarp or seed coat upon imbibition is named myxodiaspory. The outer cell layer of the fruit that has the potential to produce mucopolysaccharides is termed myxocarpy [9]. The specific type of plant undergoes myxospermy, a significant feature of the plant having the capacity to produce mucilage by commencing the differentiation of the seed coat epidermis upon fertilization. This leads to the formation of mucilage in the Golgi Apparatus, which is then secreted into the apoplastic compartment through secretory vesicles [4,10]. Furthermore, it forms a gel-like clear covering around the seed and acts as a protective covering, along with functional benefits like moisture retention, protection against harsh environmental conditions, and protection from the attack of pathogenic microorganisms. SeM is primarily composed of cellulose, pectin, and hemicellulose [11]. Seed-derived mucilage, synthesized by plants including *Arabidopsis thaliana*, basil, clary sage, and flaxseed, possesses hydrophilic properties, offering diverse applications and functional properties. The potential of the seed mucilage extends beyond the food sector. It has been used in the pharmaceutical and cosmetic sectors for peroral delivery and stabilizers, respectively [4,12,13]. This review focuses on the applications and functional properties of some selected seed mucilage sources such as tomato, fenugreek, balangu, sicklepod, basil, tamarind, garden cress, broadleaf plantain, sage, and quince. It further highlights the factors affecting the seed-derived mucilage, limitations, and prospects. Research findings on the new applications of the selected seed-derived mucilage sources have been elucidated and consolidated. For instance, novel biodegradable films from tomato SeM and gelatin at different ratios by incorporating plasticizers like polyethylene, glycerol, and sorbitol were prepared. Although it is a good option for food packaging, it was observed to be inferior to synthetic ones in terms of barrier properties and not scalable at the industrial level [14]. Carboxymethylated and thiolated sicklepod SeM developed for drug delivery was observed to improve the disintegration property in the carboxymethylated one and the bio-adhesive property in the thiolated one [15]. Additionally, the review expects further exploration in future research regarding the unknown applications and improvement in its extraction and uses in various industries. Table 1 shows the composition, benefits, and applications of mucilage from various plants.

Table 1: Sources, composition, benefits, current and potential applications of mucilage from various plants

Source	Composition (Carbohydrates)	Benefits	Current and potential applications	References
Chia (<i>Salvia hispanica</i> L.)	Glucose, galacturonic acid, xylose, arabinose, mannose	Prebiotics reduce the glycemic index	Improvement of the texture of yogurt, improving viscosity, and swelling property	[16]
Tomato (<i>Solanum lycopersicum</i> L.)	Arabinose, rhamnose, xylose, galactose, glucose and rhamnose	Antimicrobial, AOx activity	Coatings, edible films, and biodegradable packaging	[17,18]
Flax (<i>Linum usitatissimum</i> L.)	Uronic acid, rhamnose, galactose, galacturonic acid, arabinoxylan	AOx activity, antibacterial, soluble fibre, bioactive compounds, reduce cholesterol	Textural agent in cosmetics, stabilizer, edible films, fat replacer, textural modifier	[19–21]
Basil (<i>Ocimum basilicum</i> L.)	Glucose, galacturonic acid, rhamnose, mannose, glucuronic acid, arabinose and galactose	AOx activity improves seed germination, essential amino acids	Protein solubility, gelling agent, thickening agent, emulsifier, foaming agent	[22–24]
Garden cress (<i>Lepidium sativum</i> L.)	Arabinose, xylose, rhamnose, galactose, galacturonic acid	Antimicrobial, AOx effect, anti-mutagenic effect	Edible coating, egg replacement, foaming ability, emulsifier	[25–28]
Broadleaf plantain (<i>Plantago major</i> L.)	Glucose, xylose, rhamnose, galactose, arabinose and glucuronic acid	Anti-inflammatory, AOx effect, anti-infective agent	Emulsifier and foaming agent	[29,30]
Quince (<i>Cydonia oblonga</i>)	Glucuronic acid and xylose	Good barrier properties and tensile strength	Coating material for preservation, wound-healing, and inflammation reduction	[31,32]
Hibiscus (<i>Hibiscus syriacus</i>)	Galactose, glucosamine, galacturonic acid	Antifungal, antidepressant, wound healing, antidiabetic	Water holding capacity, swelling capacity, wound healing ability	[33]

(Continued)

Table 1 (continued)

Source	Composition (Carbohydrates)	Benefits	Current and potential applications	References
Okra (<i>Abelmoschus esculentus</i> L.)	D-galactose, L-rhamnose and galacturonic acid	Antidiabetic, anti-cancer, anti-hypertensive, antimicrobial	Texture modification, stabilizer, pharmaceutical excipient	[34–37]
Guar (<i>Cyamopsis tetragonoloba</i> L.)	Mannose and galactose	Diabetes management, anti-proliferative	Binding agent, fracturing fluids, corrosion inhibitor	[38,39]
Purslane (<i>Portulaca oleracea</i> L.)	Pectic substances, monosaccharides including uronic acid, galactose, glucose, arabinose, xylose, and rhamnose	Reduce cholesterol, blood glucose, modulate lipid metabolism, anti-diabetic	Intestinal infection treatment, liver and kidney inflammation treatment	[40]
Tamarind (<i>Tamarindus indica</i> L.)	Galactose, glucose, xylose	Non-toxic, biocompatible, chemically and thermally stable	Thickener, encapsulation, and emulsifying agent	[41]
Guava (<i>Psidium guajava</i> L.)	Galacturonic acid, glucose, fucose, ribose, rhamnose, and galactose	Anti-inflammatory activity, immunomodulatory activity	Use in tumor immunotherapy	[42]
Barbados gooseberry (<i>Pereskia aculeata</i>)	Galactose, arabinose, rhamnose, fucose	AOx and antimicrobial activity	Pseudoplastic behavior, surfactant, flexible film formation	[43,44]
Sage (<i>Salvia macrosiphon</i>)	Galactomannan (mannose + galactose)	High AOx activity	Stabilizer, gelling agent, and binder in cosmetics and food	[45,46]
Balangu (<i>Lallemanitia royleana</i>)	Arabinose, galactose, xylose, glucose and rhamnose	Antibacterial and AOx effect	Foam stabilizing, edible film. reduction of lipid oxidation	[47–49]

(Continued)

Table 1 (continued)				
Source	Composition (Carbohydrates)	Benefits	Current and potential applications	References
Sickle pod (<i>Cassia obtusifolia</i>)	Xylose, galactose and mannose	Enhance vision, reduce blood glucose level, immunomodulatory effect	Film formation, bio-adhesion, and drug delivery	[15,50,51]
Fenugreek (<i>Trigonella foenum-graecum</i> L.)	Glucose, xylose, rhamnose, fructose, mannose, galacturonic acid, fucose, galactose	Antidiabetic and antimicrobial	Gelling agent, binding agent, absorbent, disintegrating agent	[52,53]

2 Overview of Seed Mucilage

2.1 Tomato

Tomato (*Solanum lycopersicum* L.) processing produces an enormous amount of waste which mostly comprises seed and peel, with seeds making up 60% and peel 40% of the total waste [18,54]. A beneficial polysaccharide called mucilage primarily consists of arabinose, rhamnose, xylose, glucose, and galactose. Glucose and rhamnose surround the tomato seeds, whereas xylose forms the majority of the tomato SeM [2,55]. Owing to its polysaccharide composition, tomato SeM possesses film-forming ability, which can be used as edible packaging. It has been observed that the addition of titanium dioxide to the film increased its antibacterial activity against certain Gram-positive and Gram-negative bacteria [14]. A study reported the use of tomato SeM incorporated with shallot essential oil as an active coating to reduce the rate of physical, microbial, chemical, and color changes in *Oncorhynchus mykiss* fillet [56]. Besides, tomato SeM also finds its applications in the formulation of edible coatings and encapsulation to improve sensory properties and keep the quality of ketchup [57]. Polysaccharides extracted from black tomato pomace showed significantly higher emulsifying capacity compared to acid-extracted potato, apple, and citrus pectins. These polysaccharides may be utilized as emulsifiers and stabilizers in the food sector [58].

2.2 Fenugreek

Trigonella foenum-graecum, which is commonly known as fenugreek, belongs to the leguminous family Fabaceae. It is widely cultivated in Western Asia, Europe, the Mediterranean, and Asia for culinary and medicinal purposes. The seeds of the fenugreek add flavor to the food. The ripe seeds of the fenugreek are comprised of bioactive substances that offer a great deal in the food industry and medicine [52]. Fenugreek SeM, which is naturally available in fenugreek, helps in facilitating the hydration and germination of the seeds. It is considered to be biocompatible, non-irritating, and non-toxic biomolecules. The mucilage content is high in the fenugreek seed and exhibits antidiabetic properties [53]. Fenugreek SeM is comprised of polysaccharides along with other bioactive molecules like steroids, amino acids, alkaloids, saponins, and flavonoids. It has 45%–60% carbohydrates, out of which around 30% is soluble fiber and 20% is insoluble fiber [52,59]. The general composition of plant mucilage and its sources are shown in Fig. 1. Fenugreek SeM acts as a gelling agent and thickener (suspending agent) in the food industry [60]. The film-forming ability of the SeM enables its application in food packaging, pharmaceuticals, and various industries with great opportunities for the development of sustainable and bio-based materials [3]. It has good water solubility [61]. In pharmaceutical industries, it is used as a mucoadhesive gelling agent, binding agent, and disintegrating agent, providing great potential as an absorbent for capturing substances from the aqueous solution [52]. Recently, Hussain et al. [62] prepared a pH-responsive colloidal gel system from fenugreek SeM for better oral availability of methotrexate. Moreover, fenugreek SeM is considered to be a promising medium for oral drug delivery.

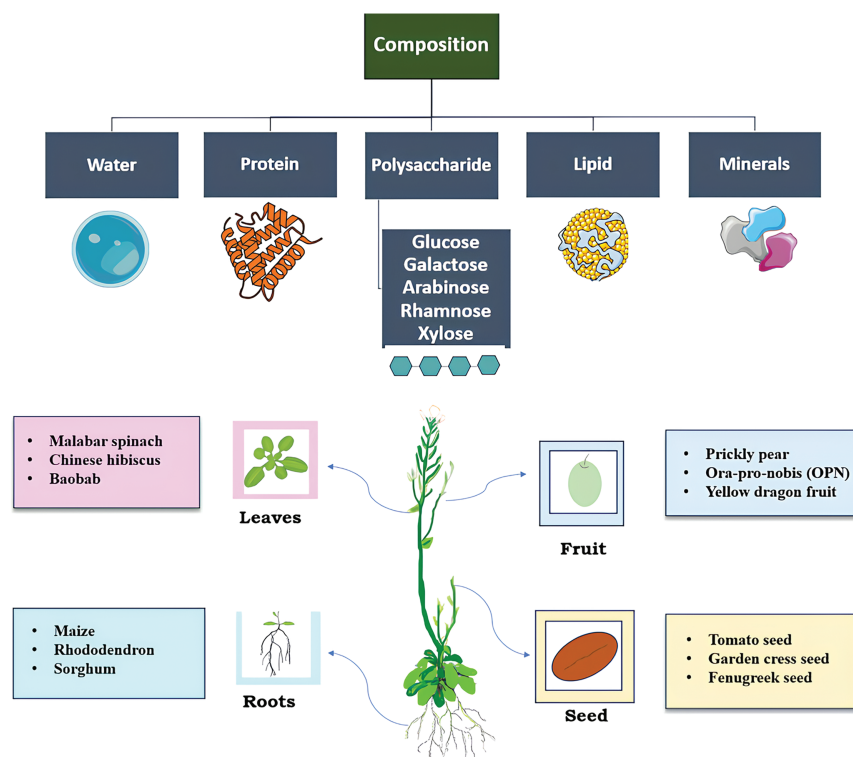


Figure 1: Various sources of plant mucilage and their composition

2.3 Balangu

Balangu (*Lallemantia royleana*) is an annual herb belonging to the family Lamiaceae. The mucilage of balangu seed is a high molecular weight polysaccharide, resulting in its many functional properties. This plant is commonly grown in Iran, Turkey, and India. The seed forms mucilage when it comes in contact with water. Traditionally, its seeds are used for many purposes, including the treatment of ailments, including inflammation and cough, as a sexual stimulant, as well as seed oil for medicinal purposes [48,49]. Balangu SeM finds its applications in various sectors due to its beneficial properties [63]. Balangu SeM is majorly composed of carbohydrates, consisting of arabinose, galactose, xylose, glucose, and rhamnose. Apart from this, balangu SeM composition includes around 9.9% ash, 9.4% moisture, 3.8% protein, and 82.56 µg GAE/mg total phenolic content [47].

Owing to its high molecular weight, balangu SeM can be used as a foam stabilizer. The SeM offers a wide range of functional properties. Given its potential to develop edible films with improved mechanical and barrier properties, it is ideal for food packaging [64]. When used in combination with cumin essential oil as an edible coating, it showed improved shelf life, reduced lipid oxidation, and microbial spoilage [48]. The SeM has antibacterial and AOx effects due to the presence of active compounds. Because of its high uronic acid and protein content, the supernatant fraction of its water-soluble polysaccharides exhibits the best emulsifying performance when fractionated according to molecular weight [49].

2.4 Sickel Pod

Cassia obtusifolia L, commonly known as sicklepod or Chinese senna, is an annual herb that belongs to the Leguminosae family. It is extensively found in Brazil and is native to West India and Central and tropical America. *Cassia obtusifolia* has many health-boosting properties like reducing hypertension, enhancing

eyesight, reducing blood glucose levels, and immunomodulatory effects [50,51]. The mucilage of sicklepod seed has been found to have polysaccharides which are useful in film formation for drug delivery and have properties like swelling capacity, mucoadhesive property, and flexibility [15,65]. The sicklepod SeM primarily consists of polysaccharides, which make up approximately 68% of its composition. The mucilage lacks steroids, starch, glycosides, tannins, and alkaloids [50]. Different fractions of sicklepod SeM have varying compositions. The fraction obtained using 30% ethanol majorly consists of branched galactomannan. On the other hand, the fraction obtained using 40% ethanol has a high concentration of xylose and a low concentration of galactose and mannose [66].

The SeM can be extracted using hot water, followed by purification and drying to get a free-flowing powder. The general method for the extraction of SeM is given in Fig. 2. Sickle pod SeM has several functional properties. The film formed using the mucilage is flexible, non-irritating, chemically stable, has good tensile strength, and mucoadhesive properties. Carboxylation and thiolation of sicklepod SeM result in the improvement of bio-adhesive properties and lower the disintegrating time for drug delivery [15,50]. The mucilage has immunomodulatory activity, showing a stimulating effect on macrophages [64]. Carboxymethyl-substituted sicklepod SeM shows improved swelling properties, flow behavior, degree of crystallinity, and reduced viscosity of aqueous dispersion [65].

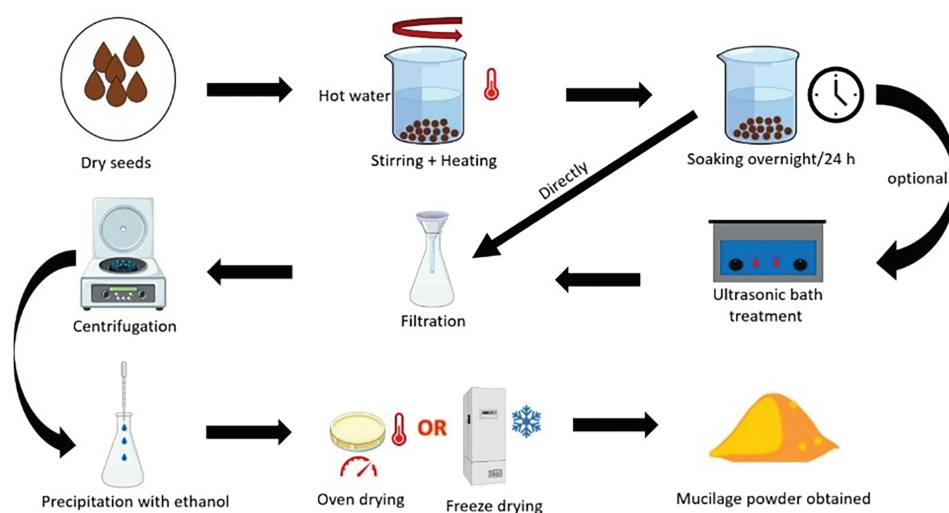


Figure 2: General extraction method of Seed mucilage

2.5 Basil

Ocimum basilicum L., which is commonly known as basil, comes under the family of Lamiaceae. It has been predominantly grown in the Himalayan region of Jammu and Kashmir, India. Upon hydration, mucilaginous substances are eventually formed around the seeds [24]. Approximately, basil SeM is comprised of carbohydrates (79.6%), lipids (9.7%), moisture (8.1%), ash (3.3%), protein (1.6%), and starch (1.53%). It consists of two major fractions, one of which is acid-stable glucomannan with a ratio of glucose to mannose of 10:2, and the other one is xylan, which has (1, 4) glycosidic linkages having acidic side chains at C-2 and C-3 at the xylosyl part. Moreover, there is also a minor portion of glucan, constituting 2.31%, and a highly branched arabinogalactan [67]. The carbohydrates of the basil SeM consist of glucose, galacturonic acid, rhamnose, mannose, glucuronic acid, arabinose, and galactose in the ratio of 3.54:2.56:1.56:0.46:0.99:0.21:0.12 M accordingly [23]. Fig. 3 depicts the structure, synthesis pathway of mucilage, and key enzymes involved in its formation.

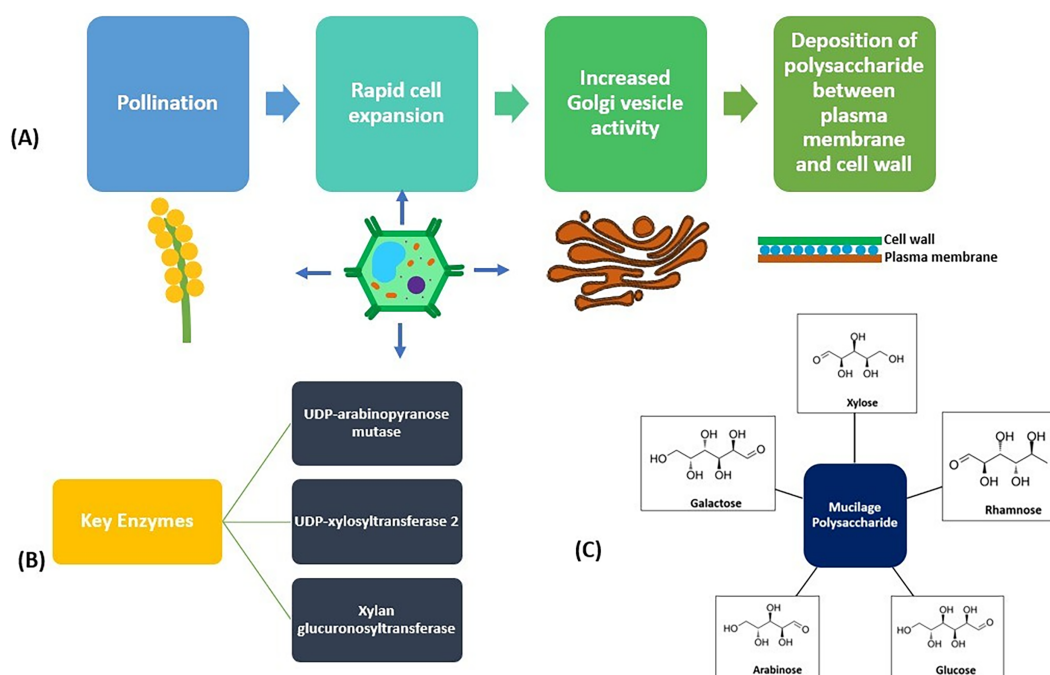


Figure 3: Depiction of structure, key steps, and enzymes involved in seed mucilage formation. (A) shows the key steps involved in mucilage synthesis. The key enzymes involved in mucilage synthesis are depicted in (B). (C) shows the structure of major polysaccharides present in seed mucilage

The highly viscous nature of basil SeM contributes to its good foaming properties [24]. Due to its low production cost, biocompatibility, eco-friendliness, and great rheological properties, basil SeM has shown great potential as a film-forming agent [68]. It has also been used in man-made heart coatings, skin operations, bio-detection systems, contact lenses, edible films, drug delivery systems, etc. [23]. According to the study conducted by Hasheminya [69], films developed from basil SeM with the incorporation of zinc oxide nanoparticles have been shown to have an effect with varying concentrations of zinc oxide nanoparticles. With the increase in the concentration of zinc oxide nanomaterials, the films are observed to have lower oxygen permeability, moisture content, water vapor permeability, water solubility, and a rise in tensile strength.

2.6 Tamarind

Tamarindus indica, also known as tamarind or Indian date, belongs to the leguminous family Fabaceae. It is predominantly grown in Asian countries like India, Thailand, Malaysia, Myanmar, and Bangladesh, and other countries like South America and Africa. India is the largest producer and exporter of tamarind. Tamarind seed is obtained as a by-product during tamarind processing. Mucilage can be extracted from these seeds, which could significantly reduce waste generation and would help in increasing the economies of the producer [70–72].

It has been found that tamarind seed contains ~72% mucilage. Tamarind SeM is composed of galactose, glucose, and xylose as the primary polysaccharides in a ratio of ~1:3:2, with a molecular weight ranging from 700–880 kDa. Essential amino acids such as valine, phenylalanine, leucine, lysine, methionine, and isoleucine are present in high concentrations [71]. Tamarind SeM comprises ash content (2.45%–3.30%), proteins (12.77%–15.40%), carbohydrates (61%–72.2%), and fat (3%–7.5%) [41]. It is made up of β -(1,4)-D-D-glucan

backbone replaced with side chains of α -(1,4)-D-xylopyranose and (1,6) linked [β -D-galactopyranosyl-(1,2)- α -D-xylopyranosyl] to glucose residues [70]. It has been found that tamarind SeM has high stability (>82%). Its particles are thermostable until 175°C [72]. It is chemically stable, biocompatible, non-toxic, edible, eco-friendly, and non-carcinogenic. Due to its high viscosity and pH tolerance across a wide range of pH and temperature conditions, and other functional properties, it is a biomaterial that is a good choice for conservation [41].

2.7 Garden Cress

Lepidium sativum L., commonly known as garden cress, is an annual herb (family Brassicaceae). It is a fast-growing herb that originated from Asia and Egypt [73]. When the seed is immersed in water, the mucilage on its coat swells up and envelopes the entire seed, creating a clear, colorless layer [74,75]. Its seeds give mucilage owing to their high polysaccharide content. The mucilage can be extracted by using hot water as the solvent. The seeds have properties like radical scavenging activity and egg re-placement [25,27]. The protein content of garden cress SeM ranges from 31.2% to 34.1%. Ash content ranges from 11.43% to 13.46%. The mucilage shows high AOX activity [25]. The polysaccharide content of garden cress is approximately 18.3%, which includes galacturonic acid, glucose, rhamnose, arabinose, and galactose. It also consists of cellulose and uronic acid [28].

Garden cress SeM has many functional properties which are useful in industry. The mucilage extracted using an ultrasonic bath showed high AOX activity (DPPH 88.9%). As compared to Butylated Hydroxytoluene, garden cress SeM showed more radical scavenging activity [25]. Microcapsules prepared from garden cress mucilage showed good retention of phenolic content. In simulated intestinal fluid, it showed high bio-accessibility of garden cress phenolic-rich extract as well as good storage stability [76]. Biopolymer extract of garden cress SeM contains functional groups like meth-oxy, carbonyl, carboxyl, and hydroxyl. The biopolymer's anionic behavior was shown by its zeta potential. These properties make the biopolymer a good coagulating and flocculating agent that can be used for the removal of turbidity from wastewater [77]. Because of its reactive oxygen species scavenging potential, it shows a high antimicrobial effect, especially against *Staphylococcus aureus*. The polysaccharides extracted from garden cress seeds also showed diminishing growth effects against cancer cell lines. It also showed an anti-mutagenic effect, possibly due to its radical scavenging activity [26].

2.8 Broadleaf Plantain

Plantago major (broadleaf plantain), belonging to the family Plantaginaceae, is a perennial herb widely distributed across the globe with various potential pharmaceutical and functional applications. Historically, it has been used in countless civilizations for wound healing, respiratory, and digestive ailments [78,79]. Mucilage from broadleaf plantain is primarily composed of high molecular weight polysaccharides. The seed's outer coat (known as the seed coat) has polysaccharides that swell when they come in contact with water, creating a densely viscous mucilage. The polysaccharides obtained from the seeds with cold water consist of arabinose, xylose, and galacturonic acid; when re-extracting the remaining material with hot water, xylose, arabinose, galactose, and galacturonic acid were obtained [30].

Broadleaf plantain SeM is a useful natural polymer that may be used for multiple purposes as an abundant polysaccharide containing functional properties. The extracts of this plant show numerous biological activities, which make them potential components for therapeutic applications. They aid in wound healing by improving tissue regeneration and reducing recovery time. These remedies demonstrate anti-inflammatory and pain-reducing effects that enable a reduction in swelling and discomfort. Additionally, their AOX characteristics safeguard cells against oxidative harm, supporting overall well-being. These extracts also have

immunomodulatory properties that regulate the immune system response, and their antiulcerogenic effect protects the stomach, thus reducing the risk of ulcers [79]. *Plantago major* SeM combined with Citrus limon essential oil coat for buffalo meat effectively reduced lipid oxidation for 10 days of storage at 4°C without affecting meat sensory characteristics [80]. Markers such as 25 inter-simple sequence repeat ISSR (Inter Simple Sequence Repeat) primers showed genetic diversity among *Plantago* species. *P. amplexicaulis* and *P. psyllium* showed the greatest variation of high levels of polymorphism (>80%) in thirty-one *Plantago* accessions from eight different species. The highest number of polymorphic bands and marker index were produced by ISSR-9, whereas the highest polymorphic information content values of ISSR-9 and IS01 indicate their effectiveness in genetic diversity assessment [81]. Another study evaluated drought risk index and marker-trait associations using ISSR and simple sequence repeats markers across multiple environments. Particularly in drought-stressed conditions, ISSRs found strong, consistent correlations with seed and mucilage characteristics and SSR markers connected to genes specific to drought. About 86% of 30 *Plantago* accessions performed better for mucilage under drought stress [82].

2.9 Sage

Wild sage seed, also known as *Salvia macrosiphon* (Lamiaceae family), has round and small seeds that form mucilage when the seeds come in contact with water [83]. It is an herbaceous plant with having strong lemon-like scent. It has high AOx as well as anti-inflammatory effects. It has about 30% uronic acid content with polysaccharides comprising mannose and galactose [46]. It consists of about 0.85% lipid, 8.17% ash, 6.72% moisture, 2.84% protein, and 1.67% crude fiber, along with 79.75% carbohydrate content [84]. It is widely utilized in the food and pharmaceutical industries. According to certain research, sage mucilage has a lot of potential as a thickening agent in food items. It also exhibits pseudoplastic properties. When *Lactobacillus casei* was encapsulated with sage SeM, its growth was enhanced [85]. The viability of *Lactobacillus rhamnosus* under stress and heat was increased by encapsulating it in this mucilage. Wild sage mucilage is utilized in a variety of applications, including as a class 1 preservative for fish, meat, poultry, and sauces. It also has antibacterial qualities, which make it a useful plant [46]. Wild sage seed gum has high-yield stress, viscosity, and strong shear-thinning characteristics [83].

2.10 Quince

Quince (*Cydonia oblonga*) is a fruit seed plant known for its high mucilage content. Quince SeM has been researched for application in the food and pharmaceutical industries due to its functional properties. Quince SeM is a water-soluble polysaccharide composed of glucuronic acid and glucuronoxylan-based substances [32,86]. Quince SeM's highly cross-linked structure endows it with a superior thickening capability compared to many other seed gums, enabling it to form viscous colloidal suspensions with aqueous solutions. Its complex yet precise macromolecular architecture is responsible for its utility as a valued source of hydrocolloids, combining cellulosic fibers and water-soluble polysaccharides, prized for numerous industrial and culinary applications requiring a high degree of viscosity [87–89]. This mucilage can be extracted using various techniques as depicted in Table 2. The water holding capacity, which includes hydrodynamic water, physically bound water, and linked water, was measured at 92.50 ± 1.63 , while the oil holding capacity, indicating oil absorption capacity, was measured at 19.30 ± 0.59 [31]. The plant has been used and prescribed in traditional Iranian medicine to treat health problems. The sedative leaves and the dysentery fruits. The seed also acts as a soothing agent for the throat and as an emulsifier for inhair-setting lotion formulations lotions [88]. Aghmiuni et al. [32] prepared a quince SeM-based scaffold, which was able to promote the adhesion of human adipose stem cells as well as the growth of fibroblasts, showing its potential application in wound dressings.

Table 2: Novel and conventional extraction and separation methods of seed mucilage obtained from different sources

Seed source	Extraction method	Solvent	Methodology	Separation method	References
Garden cress	Hot water extraction	Distilled water	Garden cress meal was stirred in DW in a ratio of 1:30, then soaked for 24 h at 80°C.	Centrifugation at 3000× g for 20 min, supernatant collected, evaporation at 60°C, precipitation in ethanol, freeze drying, and purification using sieves.	[25]
	Ultrasonic extraction	Distilled water	Garden cress meal stirred in distilled water (1:30), then soaked in an ultrasonic bath for 120 min at room temperature.	Centrifugation at 3000× g for 20 min, supernatant collected, evaporation at 60°C, precipitation in ethanol, freeze drying, and purification using sieves.	[25]
Tomato	Ultrasonic extraction	Distilled water	Seeds added to DW (1:40), agitated and kept for 8 h at 4°C, then placed in ultrasonic bath for 20 min at 100 W and 40 kHz.	Centrifugation for 5 min at 8000× g, vacuum drying of mucilage at 50°C, and obtained powder was stored in the refrigerator.	[90]
	Ultrasonic extraction	Distilled water	The seeds were added to DW (1:40), agitated for 120 min, and stored at 4°C overnight, then placed in an ultrasonic bath for 20 min.	Centrifugation for 2 min at 8000× g, evaporation of mucilage at 45°C using a rotary evaporator, and final drying at 50°C using a vacuum oven.	[14]
Sickle pod	Hot water extraction	Distilled water	Seeds milled to remove the seed coat, obtained endosperm (100 g), boiled with DW for 60 min, then soaked at ambient temperature overnight.	Solution filtered using muslin cloth, precipitated using acetone, filtered, and oven dried at 45–50°C, then converted to powdered form and passed through a sieve.	[15]

(Continued)

Table 2 (continued)

Seed source	Extraction method	Solvent	Methodology	Separation method	References
Balangu	Hot water extraction	Distilled water	Seeds milled to obtain endosperm; the endosperm (100 g) was heated with DW at 60°C, then soaked at ambient temperature for 24 h.	Solution filtered using muslin cloth, precipitated using the same volume of acetone, filtered and oven dried at 45–50°C, then grinded into powdered form and passed through a sieve.	[50]
	Hot water extraction	Distilled water	Purified seeds were added to water in the ratio 1:20 and stirred for 3 h at pH 7 and 50°C temperature.	Solution filtered through cheesecloth, centrifugation for 15 min at 3000 rpm followed by oven drying for 6 h at 50°C.	[48]
	Hydrochloric acid extraction	0.1 N HCl	Dry seeds added to 0.1 N HCl (1:10), heated until the seeds are discoloured, followed by.	Addition of 96% ethanol (20 mL), kept in refrigerator for 5 h, precipitate removed from mucilage.	[91]
Quince	Water extraction	Distilled water	Seeds were washed with ethanol, dried, then added to DW (1:30) and blended for 15 min, 45°C at 1100 rpm for extraction.	Solution filtered with cheesecloth and obtained mucilage, stored in the refrigerator.	[92]
	Water extraction	Milli-Q water	Seeds were soaked with Milli-Q water (4:75) and extracted with a rotary evaporator at 30°C overnight.	Solution filtered with gauze and freeze-dried.	[93]
	Water	Deionized water +0.02%(w/v) sodium azide	Dry-cleaned seeds mixed with solvent (1:100) and stirred at 60°C for 2 h, then further soaked for 12 h.	Solution filtered using a linen cloth, oven dried at 50°C for 24 h, and powdered using a mortar and pestle.	[94]

(Continued)

Table 2 (continued)

Seed source	Extraction method	Solvent	Methodology	Separation method	References
Wild sage	Water extraction	Water	Sage seeds soaked in water (1:15) at 25°C for 20 min with a pH of 5.5.	Separation of the mucilage using the laboratory extractor, centrifuged at 7200 rpm for 10 min to separate the impurities from the crude mucilage, dried at 70°C in an oven, milled, and cooled down in a desiccator at 4°C.	[85]
			The 20:1 ratio of water to seeds was stirred in the stirrer at 50°C for 20 min with a pH of 7.	Dehydrated the sage seeds in an oven at 50°C, and milled.	
Basil	Maceration	Water			[46]
	Response Surface Modelling (sieving as a mechanical technique)	Distilled water	Basil seeds immersed in the water (1:18–1:77), whose pH is adjusted to 8 using 0.2 M NaOH or HCl solutions, are stirred on the magnetic stirrer at constant temperature (40–91°C).	Separated by passing through the mesh screen of size 10, dried at 50°C for 10 h, and separated the adhered mucilage using 40 mesh screens.	[24,95]
	Ionic liquid extraction	Ionic liquids (Pyridinium-based ionic liquids)	Dried basil seeds soaked in the heated (110°C) of ionic liquid (3:100), stirred at 300 rpm at same temperature.	Filtered the contents after 2 h, dissolved basil SeM in the filtrate, is regenerated using 30 mL of acetonitrile, centrifuged at 4000 rpm for 10 min.	
	Chemical extraction	Concentrated hydrochloric acid (HCl) diluted with distilled water at a ratio of 1:2 v/v	Dried basil seeds were soaked in the dilute acid solution (0.1:2), stirred for 5 min.	Filtered using a sieve, washed under running water, and dried the obtained mucilage at 25°C at 40% RH.	[67]

(Continued)

Table 2 (continued)

Seed source	Extraction method	Solvent	Methodology	Separation method	References
Broadleaf plantain	Exhaustive Extraction	Water	Seeds were added to water (1:100) in a jacketed glass vessel, which is connected to an ultra-thermostatic bath at 80°C for 1 h under magnetic stirring.	Filtered using organza fabric using a ceramic Buchner funnel placed on top of an Erlenmeyer flask connected to a vacuum pump.	[96]
	Ultrasound-assisted Extraction	Distilled water	The 400 W at 35°C for 30 min is maintained for sonication procedure, filtration of the solution, with a 1:10 ratio of seed: water at 75°C for 40 min, and the seeds and water were blended.	Segregated the mucilage using an extractor, filtered and precipitated the obtained mucilage with three volumes of 96% ethanol, filtered and dried the precipitate at 45°C for 16 h	[30]
Tamarind	Hot water	Distilled water	Milled seeds added to DW (1:10), contents poured into 800 mL DW and agitated for 40 min (80°C) and left standing for 24 h (20°C).	Centrifugation for 5 min at 50 rpm, followed by separation of supernatant.	[41]
	Hot water	Distilled water and bi-distilled water	Tamarind kernel powder soaked and stirred in DW(1:10) for 10 min, addition of bi-distilled water (added in 1:40 seed to water ratio) and constant heating at 80°C for 60 min, and kept for 24 h at 20°C.	Centrifuged at 524× g for 8 min, decantation of supernatant, and cooled.	[72]
Fenugreek	Ultrasound-assisted extraction	Deuterium oxide (D ₂ O)	The 1:55 mass ratio of solid to water as the solvent, placed in the ultrasound bath and operated at 100 W, 37 kHz, and at 55°C for 30 min.	Filtration of the mixture to obtain mucilage.	[52]

Notes: DW, Distilled Water; rpm, revolutions per minute; RH, Relative Humidity; HCl, Hydrochloric acid; NaOH, Sodium hydroxide.

3 Research Studies Elucidation

Mucilage from tomato seeds, sage, and fenugreek has shown extensive applications in the food, pharmaceutical, and cosmetic sectors. A study investigated the use of tomato SeM as a suitable material for the formation of biodegradable films. It mainly focused on the use and effects of glycerol and cellulose nanofibers on film properties. With the addition of 5% glycerol and 10% cellulose nanofibres, the thermal stability, mechanical strength, and barrier properties improved. Water and oxygen resistance was accelerated with the addition of cellulose nanofibers. The films formed had strong AOX and antimicrobial properties along with a UV-blocking effect [2]. A pH-responsive hydrogel was formed using fenugreek SeM to increase the oral bioavailability of methotrexate. The hydrogels were swollen maximum of around 384.7% at pH 7.4 and provided controlled methotrexate release for up to 24 h. Toxicity tests were performed, which did not show any harmful effects on normal cells or animal cells, and the hydrogels were less toxic to cancer cells compared to free methotrexate [62]. Sickie pods can be used as an additive form of drug delivery. A biodegradable film was formed, which showed a smooth surface on scanning electron microscopy, and X-ray diffraction showed an amorphous structure. *In vitro* degradation, simulated body fluids, and oral acute toxicity showed that the sicklepod mucilage is a safe additive for drug delivery [50]. The antibacterial activity of basil SeM, a green wound dressing, was increased with the addition of aloe vera extract. The mucilage was cross-linked using malonic acid, which increased the stiffness and decreased porosity, swelling, and water retention to improve dimensional stability. The sponge cytotoxicity, mechanical characteristics, and hydrophilicity were unaffected by the addition of aloe vera extract. It considerably increased the antibacterial activity against *Pseudomonas aeruginosa* and *Staphylococcus aureus* [97].

Tamarind SeM was used as a wall material for the encapsulation of sesame oil using the spray drying technology. Two distinct wall-to-core ratios (1:1 and 1:2) were evaluated, which further revealed that both kinds of microcapsules exhibited good encapsulation efficiency and free-flowing characteristics (91.05% for the 1:1 ratio and 81.22% for the 1:2 ratio) [72]. Garden cress SeM was used as a natural nutraceutical for protection against enterocolitis. The mucilage that was extracted using the ultrasonication technique showed strong AOX activity. Rats that were pre-treated with the mucilage before receiving indomethacin showed lower levels of intestinal TNF- α , plasma LDH, and erythrocyte sedimentation rate (ESR) than rats that were not treated. The intestinal malondialdehyde (MDA) showed lower levels, whereas intestinal reduced glutathione (GSH) was high [25]. The mucilage extracted from *Plantago major* L. seed was used as a natural cosmetic ingredient. The maximum yield of 18.4% mucilage was achieved under ideal circumstances at conditions of 140.5 min, a 0.0284 solvent-to-seed mass ratio, and a temperature of 80.2°C after the mucilage was removed and dried. The dried substance showed a structure resembling carbohydrates that was thermally stable. The mucilage showed a pseudoplastic rheological profile when it was gelled, re-simulating commercial polymers such as xanthan gum [96]. The addition of quince SeM to yogurt resulted in enhanced sensory properties. The addition of mucilage powder at 0.05% and 0.1% was considered acceptable by the panelists in terms of mouthfeel, flavor, and odor scores, however, increased amounts of SeM resulted in a decline in sensory qualities [98]. Table 3 shows potential applications of seed mucilage as per different studies.

Table 3: Potential applications of mucilage extracted from different seeds as per the observations made according to different studies

Source of seed	Application	Procedure	Observation	References
Basil (<i>Ocimum basilicum</i> L.)	Development of natural -based wound dressing with antibacterial effect	Basil SeM hydrogel sponge (no incorporation of ZnO-nanomaterial) is cut into 1 cm disc-shaped and placed on the agar plate having <i>Staphylococcus aureus</i> and <i>Escherichia coli</i> and incubated for 24 h/37°C.	Antimicrobial effect was not observed.	[99]
		Basil SeM hydrogel sponge + ZnO-nanoparticle at various levels (10 wt%, 20 wt%, 30 wt%, 40 wt% and 50 wt%), incubated at 37°C/24 h.	Exhibited antimicrobial properties against <i>Staphylococcus aureus</i> and <i>Escherichia coli</i> , which is measured as an inhibition zone in diameter.	
		Apricots are immersed in the solution containing 0.1 % Basil SeM for 5 min at ambient temperature and dried for 2 h, stored at chilling conditions (2°C).	Little loss of weight was observed, firmness was maintained, a reduction in TSS level, ethylene production, and a low respiration rate.	
Fenugreek (<i>Trigonella foenum-graecum</i> L.)	Formation of active biofilms to enhance the shelf life of fresh fruits	Fruits are treated with Basil SeM (0.1%) + Aloe vera gel (30%) solution for 5 min and dried for 2 h/25°C, which is then stored at 2°C.	Less weight loss, maintaining the firmness of the fruit, delayed ethylene production and maintaining the respiration rate at a low level, reduction in juiciness, and sweetness level.	[52]
		CMC 0.4% w/v + Fenugreek SeM powder (1% w/v) + glycerol (0.4% w/v) in distilled water poured on a petri plate of 60 mm diameter.	Moisture content of the film is slightly higher, less thickness, low water vapour permeability value, slight change in the retention of natural colour on the coated fruit (apple).	

(Continued)

Table 3 (continued)			
Source of seed	Application	Procedure	Observation References
Tamarind (<i>Tamarindus indica</i> L.)	Emulsifying agent	CMC/Fenugreek SeM powder mixture solution + Rosemary essential oil at various levels (1%, 2%, and 3% v/v) combined for 3 min at 12,000 rpm, centrifugation is done for 3 min at 8000 rpm, spread onto petri plates for 24 h.	Less moisture and an increase in inhibition zone against <i>Escherichia coli</i> and <i>Staphylococcus aureus</i> with the increase of rosemary essential oil concentrations, an increase in thickness, a high water vapour permeability value, and no change in colour or shape of the fruits coated with the films.
		Peroral delivery of methotrexate via poly methacrylate pH-receptive hydrogel attached with fenugreek SeM	[62] Release of methotrexate is highly influenced by the concentration in the formulations; high concentration of fenugreek SeM results in a reduction in the release of methotrexate.
		For the evaluation of emulsifying ability, 10 mL of corn oil + 150 mL of tamarind SeM at different levels (0.2% w/v, 0.8% w/v, 1% w/v, 0.6% w/v) was agitated for 3 min at 6400 rpm and centrifuged at 524× g for 10 min.	[72] Change in the ratio of dried tamarind SeM/volume of corn oil affects the emulsifying capability and emulsion strength. When the ratio increased, the emulsifying capacity rose, and the emulsion stability dropped.

(Continued)

Table 3 (continued)			
Source of seed	Application	Procedure	Observation References
Tomato (<i>Solanum lycopersicum</i> L.)	Active coating on trout fish fillet	For the estimation of emulsion stability, the mixed emulsions were heated for 30 min at 80°C and cooled down, and were centrifuged at 524× g for 10 min.	The ratio of tamarind SeM (wall material): sesame seed oil (core) affects the encapsulation potency. With the rise of the ratio of wall material and core, the encapsulation capacity grows.
		Nanoencapsulation of sesame seed oil Tamarind SeM + sodium azide (0.3% w/w) solution, oil in water emulsions (Em1 & Em2 at different ratio) of tamarind SeM solution: sesame seed oil mixed at 6400 rpm with the time duration 10 min, spray dried the emulsions which got microencapsulated (Mec 1 and Mec 2) during the process is then stored above phosphorus pentoxide in desiccators. Coating solution: 2% (w/v) tomato SeM solution + 2% (w/v) whey protein isolate at different concentrations with the addition of polysorbate 80 (shallot essential oil-based) and glycerol. The trout fish fillets were submerged in the coating solution for 2 min and covered in polyethylene and stored in cold storage (4°C) up to 16 days.	[72] [90]

(Continued)

Table 3 (continued)

Source of seed	Application	Procedure	Observation	References
Wild sage (<i>Salvia macrosiphon</i>)	Capsulation of <i>Lactobacillus rhamnosus</i> (ATCC 53103) was added to the date yogurt	<i>Lactobacillus rhamnosus</i> settlements which was obtained after the centrifugation (at 4500 rpm for 10 min) was rinsed two times using 0.1% peptone water, made up the volume up to 5 mL with normal saline, bilayer encapsulation (15 mL of 1.5% Sodium alginate as first layer, wild sage mucilage as second layer at different concentrations (0.8%, 0.6%, 0.4%, and 0.2%)) via extrusion method.	The capsulation potency was observed to be the highest in wild SeM (0.8%) concentration, with the value of 97.98%, which indicates that the capsulation efficiency increases with the increase in concentration. It enhances the texture, low detrimental effect on the added food product, two-fold layer protects probiotic cells from inhospitable conditions like cold storage, low pH, heat, etc.	[46]
Garden cress (<i>Lepidium sativum</i>)	Edible coating in potato fries	Potato segments dipped in mucilage for 5 min (treatment 1). Potato segments dipped in ascorbic acid+ mucilage (250 ppm) for 5 min (treatment 2).	Decreased weight loss and oil uptake, firm texture, and slowed browning.	[101]
	Nutraceutical are effective against enter-colitis	Three groups were formed, consisting of six rats each, group one served as a control, group two was given a solution of 6 mg indomethacin in 5% Sodium bicarbonate per kg per day for a week, and group three was given garden cress SeM for 14 days before and along with the indomethacin treatment.	More reduction in weight loss and oil uptake, firmer texture, and slower browning compared to treatment 1. Because the rats provided with the mucilage showed decreased intestinal malondialdehyde and more intestinal reduced glutathione, the mucilage extracted using an ultrasonic bath could help prevent enterocolitis.	[25]

(Continued)

Table 3 (continued)			
Source of seed	Application	Procedure	Observation
Balangu (<i>Lallemantia royleana</i>)	Aerogel containing paracetamol for drug delivery	Alcogel made from balangu SeM placed in paracetamol solution(ethanol-based) till equilibrium was reached and alcogel orifices were fully filled, followed by supercritical drying.	Balangu SeM aerogel initially released paracetamol rapidly, gradually decreasing due to drug entrapment, and eventually sustaining a 4 h release, demonstrating its ability to control drug release behavior. [102]
	Antimicrobial coating for beef	Cumin essential oil added to balangu SeM at 2%, 1.5%, 1%, 0.5%, and 0%. Slices of beef dipped for 1 min in each coating solution and stored for 9 days at 4°C.	Coated beef showed lower microbial count, better texture, inhibition of oxidation of lipids, reduction in pH and better moisture retention, the slice coated with 2% cumin essential oil showed the best effects compared to others. [48]
Sickle pod (<i>Cassia obtusifolia</i>)	Medium for drug delivery	Three formulations of tablets were prepared, containing 10% w/w sickle pod SeM in formulation 1, 10% w/w carboxymethylated sickle pod SeM in formulation 2% and 10% w/w CMC in formulation 3 (standard).	Carboxymethylated SeM tablet had shorter disintegrating period compared to standard and non-carboxymethylated tablet, hence can be potentially used for drug delivery. [15]

(Continued)

Table 3 (continued)			
Source of seed	Application	Procedure	Observation
Quince (<i>Cydonia oblonga</i>)	Vehicle for sustained drug release	Carboxymethylated sickle pod seed gum beads were prepared which were packed with the drug diclofenac sodium, cross-linked with calcium chloride and Eudragit L 100 used as a coating.	The 96.19% of the drug was released in simulated intestinal fluid for 24 h, 7.56% of it was eliminated in simulated gastric fluid. coating beads with Eudragit L100 gives gastro resistance, and the beads were able to sustain the release of the drug in alkaline pH for the entire day.
	Yogurt preparation with mucilage powder	Quince SeM added to raw milk (40°C) at 0.05%, 0.10%, 0.15%, and 0.2% levels, followed by pasteurization (85°C/20 min), cooling (43°C), inoculation, incubation (43°C), and further cooling and storage (4 ± 1°C).	Addition of quince SeM enhanced yogurt quality (0.05% and 0.1%) by reducing syneresis and enhancing the growth of <i>L. bulgaricus</i> .
	Edible coating for mandarin preservation	Coating prepared from mucilage (1% w/v) and glycerol (35% w/v), mandarin slices coated by immersion for 2 min and drainage of the excess liquid, followed by drying for 1 h using a forced air dryer and stored for 10 days at 4°C.	Coated samples showed preserved sensory properties, color, AOx and phenolic content, halt softening, and loss in weight and extension in shelf life by a week.

(Continued)

Table 3 (continued)			
Source of seed	Application	Procedure	Observation References
Broadleaf plantain (<i>Plantago major</i> L.)	Emulsifier and foaming agent	Plantain SeM dispersed in water at 0.3%, 0.5%, and 1% w/v to prepare the continuous phase, sunflower oil added to the continuous phase at 1200 rpm, and homogenized at 20,000 rpm for 6 min (for testing emulsifying behavior).	Continuous phase with higher concentration resulted in higher emulsifying capacity, lower oil droplet size and high zeta potential. [103]
		The 50 cc of 1% whey protein concentrate added to 50 cc of aqueous extracts of plantain SeM (0.3%, 0.5% and 1% w/v) each and whipped for 1 min at 20,000 rpm (for testing foaming properties).	
	Quality enhancer in non-fat yoghurt	Skim milk powder was added to distilled water, followed by pasteurization and cooling. plantain SeM was added (1%, 3%, and 5% w/v), starter culture was added and the mixture poured into cups followed by incubation, cooling and storage.	Foaming stability increased with increase in mucilage concentration while foaming capacity decreased with an increase in mucilage concentration. The resulting yoghurt showed decreased whey separation and syneresis, improved viscosity and gel-formation, high acidity, and retention of sensory properties. [104]

Notes: wt%, percentage weight; w/v, weight by volume; CMC, carboxymethylcellulose; rpm, revolutions per minute; cc, cubic centimeter; w/w, weight by weight.

4 Factors Affecting the Yield of Seed Mucilage

Based on the study undertaken, it has been reported that factors such as time, temperature, and water/seed ratio have a significant impact on the extraction yield of SeM. The highest yield (20.5 g/100 g) of basil SeM using an aqueous extraction method has been observed at a temperature of 50–65°C and an extraction time (2–3 h). The yield also increased with the increase in water/seed ratio (30:1) [95]. A study utilizing response surface methodology for the extraction of *Plantago major* SeM found that maintaining a pH of 6.8, a seed-to-water ratio of 1:60, and a temperature of 75°C resulted in a maximum yield of 15.18%. It also affected the functional properties, including foam stability, water absorption capacity, emulsion stability, and solubility [105]. In the case of the extraction of mucilage from *Ximenia americana* seed, the optimum conditions to attain the highest yield of 17.31% were a water/seed ratio of 37.62:1 v/w, a temperature of 65.06°C, and an extraction time of around 1.5 h [106]. Besides these factors, the extraction methods employed also play an important role in determining the yield of mucilage. Extraction methods like ultrasound and microwave are considered green technology. They are less time-consuming, requiring little to no use of organic solvents and full automation as compared to traditional extraction methods. The use of organic solvents and pressing in the ultrasound technique increases the yield but produces organic solvent residues. It has been found that an increase in the stirring time of the raw material increases the yield of mucilage [107]. As stated in the study conducted by Shiehnezhad et al. [108], it has been reported that mucilage recovery is slightly higher in the case of microwave-assisted extraction ($17 \pm 0.14\%$) than the conventional extraction ($14.53 \pm 0.25\%$) when both were provided with optimum conditions.

5 Limitations

The films that were developed using seed mucilage with the incorporation of plasticizers are not scalable as they are inferior in terms of barrier and mechanical properties compared to synthetic ones [17]. In addition, the lipophilic nature of mucilage is also one of the factors limiting its uses in industries [2]. Microwave-assisted extraction is known for high-yield extraction (approx. 31.8%). However, it has been found to reduce the apparent viscosity and molecular weight, leading to the degradation of the mucopolysaccharides. Although ultrasound-assisted extraction has been used predominantly for the extraction, it still degrades the quality of the mucilage [13]. Extraction of mucilage (chia seed) using the conventional method reduces the extraction yield due to the partial removal of mucilage from the sources [109].

A decrease in the phenolic content occurs during the process of encapsulation. It can be due to the drying method that was employed [76]. Particle size influences the film-forming ability of the mucilage. The larger the particle size, the more it is prone to microbial attacks [56]. Although seed mucilage is packed with diverse applications that promote sustainability, further studies regarding the effect of antimicrobial activity on a large number of microbes and sensory aspects need to be carried out [52]. Titanium dioxide (0%, 0.5%, and 1%) nanoparticles were incorporated with different proportions of tomato SeM and gelatin. As the proportion of tomato SeM increased, changes such as an increase in color differences and yellowness index were observed. Contrarily, a decrease in lightness and whiteness index was observed. Significant inhibitory and deadly effects against a variety of bacteria were noted when the concentration of titanium dioxide was increased to 1% [17]. During the extraction of mucilage from chia seeds, incomplete removal or detachment occurs, which reduces its yield. The yield and quality of chia mucilage are influenced by extraction parameters such as temperature, duration, and water-to-seed ratio [109].

6 Future Aspects

Seed mucilage has great potential for use in various industries. The functional properties of seed mucilage can be enhanced by blending it with other natural polymers. More research can be done on making

stimuli-responsive hydrogels which can be used for smart drug delivery in response to factors such as temperature, pH, and pressure. Nanoparticles can be used as a seed coating for improved seed hydration which can lead to better seed germination, they can also act as a carrier for fertilizers, and the coating which contains antimicrobial properties can act as a barrier that can protect the seeds from pathogens and other bacterial growth. Research is required for the commercialization of products that can be made using seed mucilage. It can completely replace synthetic stabilizers, thickeners, and emulsifiers in food products. It can be used in plant-based meat alternatives such as gelatin or egg substitutes. It can replace synthetic polymers as bio-based adhesives and gels. The seed mucilage being hydrating, can be used to produce natural and biodegradable cosmetic products such as hair gels, and skin-care products. It can also have a thriving future in the nutraceutical industry. The mucilage obtained from different seeds can also act as a natural flocculant to purify water. Fig. 4 depicts a graph showing the approximate number of papers related to seed mucilage published each year from 2015 to 2024 (data taken from the Scopus database using search terms “seed mucilage” and “plant seed mucilage” while excluding the papers published before 2015 and after 2024).

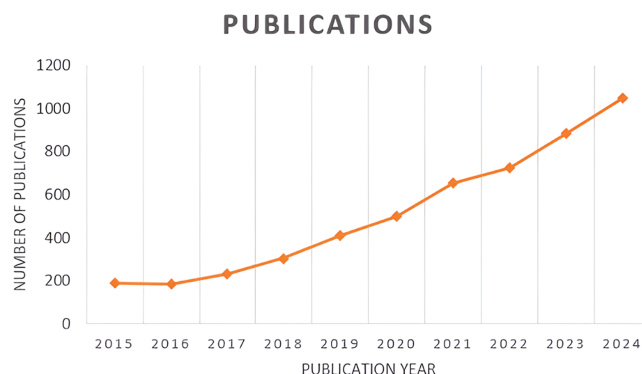


Figure 4: A line graph illustrating the approximate number of seed mucilage-related papers published annually between 2015 and 2024 as per Scopus database

7 Conclusion

Seed mucilage has become a promising biomaterial that is sustainable and biodegradable. From the food and pharmaceutical industries to the environmental and cosmetic fields, mucilage utilization has increased in the past few years. Seed mucilage possesses many important functional properties that can pave the way for its extensive use, such as film-forming ability, water retention, and antioxidant potential, making it an ideal component for developing eco-friendly products. Being biodegradable, it can serve as a possible replacement for various artificial additives, contributing to sustainability and environmental protection. Despite its promising applications in various sectors, a few challenges need to be addressed, such as optimization of its mechanical and barrier properties, such as low tensile strength, high moisture sensitivity, inconsistent permeability, water and moisture resistance, and oil permeability. Seed mucilage is not only a biodegradable alternative to synthetic polymer but also a sustainable solution to many environmental problems. Many of these seeds come under the waste category, and if they are used to produce mucilage, they can act as a profitable by-product of industries. A few mucilage-rich seeds have been explored; however, it is clear that more research is required to uncover the full potential of the mucilage of these seeds and for them to be effectively used in industries.

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