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Potential of Okra Mucilage by Employing As a Natural Polymer

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ABSTRACT:
Okra mucilage, a natural polysaccharide-rich biopolymer extracted from Abelmoschus esculentus, has garnered significant attention as a versatile, biodegradable, and biocompatible polymer with extensive pharmaceutical and industrial applications. This review comprehensively discusses the physicochemical properties, extraction methods, and polymer characteristics of okra mucilage that confer excellent swelling, viscosity, mucoadhesive, and film-forming abilities, making it suitable for drug delivery and food packaging. Its intrinsic bioactivities such as antioxidant, antimicrobial, and anti-inflammatory effects further augment its therapeutic potential. The review highlights the influence of polymer concentration on drug release kinetics, demonstrating okra mucilage's capacity to modulate immediate and sustained release profiles. Safety and toxicological evaluations affirm its non-toxic nature and wide applicability. Patent literature and current regulatory status are critically examined, underscoring the need for further standardization and inclusivity in Pharmacopoeias.Challenges including batch variation, extraction scalability, stability concerns, and regulatory gaps remain hurdles to industrial adoption. Future prospects are promising with ongoing advancements in nano-formulations, polymer blends, clinical validations, and sustainable processing techniques. Okra mucilage's potential extends beyond pharmaceuticals into eco-friendly biodegradable packaging, offering a sustainable alternative to synthetic polymers. This review envisions okra mucilage as an innovative natural polymer that can transform drug delivery and packaging sectors, provided that challenges related to quality control and regulatory acceptance are adequately addressed.

KEYWORDS: okra mucilage, drug delivery, biodegradable polymer, mucoadhesive properties, regulatory challenges.

I. INTRODUCTION:

Abelmoschus esculentus L., often known as okra, belongs to the Malvaceae family, which is sometimes known as the hibiscus or mallow family. In roughly 243 genera, this family includes over 4,255 species of trees, shrubs, and plants. Several varieties of decorative hibiscus, cotton (Gossypium species), and cocoa (Theobroma cacao) are well-known products of this family and are economically significant plants(1).Common names for okra include lady's finger, bhindi, Okura, quimgombo, bamia, gombo, and lai long ma, suggesting its widespread use and cultivation over many regions(2).In the 12th century, okra was widely cultivated by the Egyptians and then expanded throughout the Middle East and North Africa. It is said to have originated close to Ethiopia(3). Okra's scientific name is alternatively spelt Abelmoschus longifolius or Abelmoschus bammia.Okra's leaves and stems have soft, fine hairs, which is a trait shared by other members of the Malvaceae family. The family name "mallow" is derived from the Latin word malva, which was originally used to describe several similar species. This botanical lineage highlights the importance of okra as a food crop and a source of bioactive substances for industrial and pharmaceutical uses, while also demonstrating its similarities to a wide range of plants valued for their medicinal, industrial, and nutritional properties(4) such as digestive aids, astringents, aphrodisiacs, and remedies for gonorrhoea, dysentery, and urinary tract problems. According to reports, the seeds have antifungal and anticancer qualities, and extracts from young pods have moisturising and diuretic benefits(5)

Extracted from Abelmoschus esculentus, okra mucilage is a polysaccharide-rich biopolymer that is non-toxic, biodegradable, and non-irritating, making it a safer alternative to many synthetic excipients commonly employed in medicine formulations(6). Inertness and environmental friendliness, especially in oral and topical medicines, satisfy pharmaceutical needs. The gelling, thickening, emulsifying, and film-forming properties of okra mucilage are excellent. In tablets and other dosage forms, these characteristics are critical for stabilisation, regulated drug release, and efficient binder and disintegrant activity. Moreover, the intrinsic biological qualities of okra

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polysaccharides, such as their immunomodulatory, antidiabetic, and antioxidant actions, might enhance patient health and the effectiveness of medications(7).Polymers derived from okra have demonstrated a remarkable ability to alter release patterns, enhance the stability of active chemicals, and improve bioavailability in drug delivery systems. In particular, its mucilage has been demonstrated to allow for tailored release and shield sensitive drugs from severe gastric conditions in colon-specific pharmaceutical systems. As worries about the drawbacks and cost of synthetic polymers increase, okra's natural origin, affordability, and regulatory preference provide additional impetus for its development. Okra mucilage's many biological and physicochemical properties promote its use in sophisticated drug delivery matrices, microencapsulation techniques, and sustained-release forms in conjunction with other bio-polymers. Since okra is a natural polymer, a large amount of scientific, functional, and safety evidnce strongly supports its use in pharmaceutical innovation(8).

Fig no.1: Okra plant(Abelmoschus esculentus)

CHEMISTRY ANDEXTRACTIONOF OKRA MUCILAGE:

Botanical description and chemical composition of okra mucilage:

The thick, viscous mucilage of okra, made mostly from the pods, stems, and leaves of Abelmoschus esculentus, or okra, is composed primarily of natural polysaccharides. Monosaccharides such as D-galactose, L-rhamnose, galacturonic acid, mannose, glucose, arabinose, glucuronic acid, and xylose make up its makeup and are commonly associated with proteins and minerals(6). Because of the high hydrophilia of these polysaccharides, the mucilage dissolves easily in water but is insoluble in organic solvents. Because of its composition, okra mucilage has a unique viscosity and can form gels. These gels have emulsifying and foaming properties and can absorb wax and water, making them useful in food, medicinal, and nutraceutical applications.Okra mucilage also has flavonoids and phenolic compounds, which contribute to its antioxidant properties and health advantages like anti-inflammatory and hypoglycaemic effects, making it a significant functional ingredient in food and medicine(9).

Methods of extraction and purification:

Mucilage was isolated from Abelmoschusesculentus fruit. In order to remove any dirt, the fruit was first cleaned with water before being grinded in a mixer. After being soaked in warm water for four hours, the material was cooked for two hours and then left aside for two hours to allow the mucilage to flow into the water(10). The mark was eliminated from the filtrate by squeezing the material in a muslin bag after two hours. The mucilage was separated, dried in an oven at roughly 45 degrees Celsius, pulverised, and run through sieve # 80 after an equal volume of ethyl alcohol was added to the filtrate to precipitate it. The desiccator was used to keep the powdered mucilage until it was needed again(11).

CHARACTERIZATION TECHNIQUES:

Determination of carbohydrates: Molisch's reagent was added to an aqueous extract, and then sulphuric acid was added. Carbohydrates were present at the intersection where the violet hue ring emerged(12).

Ash values:

$$\text{Total ash} = \frac{\text{weight of ash}}{\text{weight of polymer}} \times 100$$

$$\text{Acid insoluble ass} = \frac{\text{weight of acid insoluble ash}}{\text{weight of dried powder}} \times 100$$

$$\text{Water soluble ash} = \frac{\text{weight of water}}{\text{weight of dried powder}} \times 100$$

(13)

pH determination:A pH meter was used to measure the pH after a 1% w/v dispersion of the sample in water was shaken for five minutes(14).

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FTIR: The FTIR spectrum of okra mucilage was captured. An IR spectrophotometer made by Brucker was used to analyse the materials. The frequency range of 4000-400 cm−1 was used to scan the spectra(15).Two distinctive peaks between 700 and 1316 cm-1 make up the finger print region of the spectrum, which is ascribed to the stretching of the C-O bond. The water's O-H bending was attributed to the band at 1604 cm-1. The 1521 contribution of carbonyl stretches. Ester connections are present in the 98 cm-1 area. Weak stretches in the 1650–1690 cm-1 region would indicate that lignin is mostly responsible for this.

X-ray powder diffraction:AEG's almost entirely amorphous nature is confirmed by the existence of many halos with weak peaks in its X-ray diffractogram (Figure 1). The DSC's finding that AEG only displays an amorphous section is supported by the XPRD's conclusion(16).

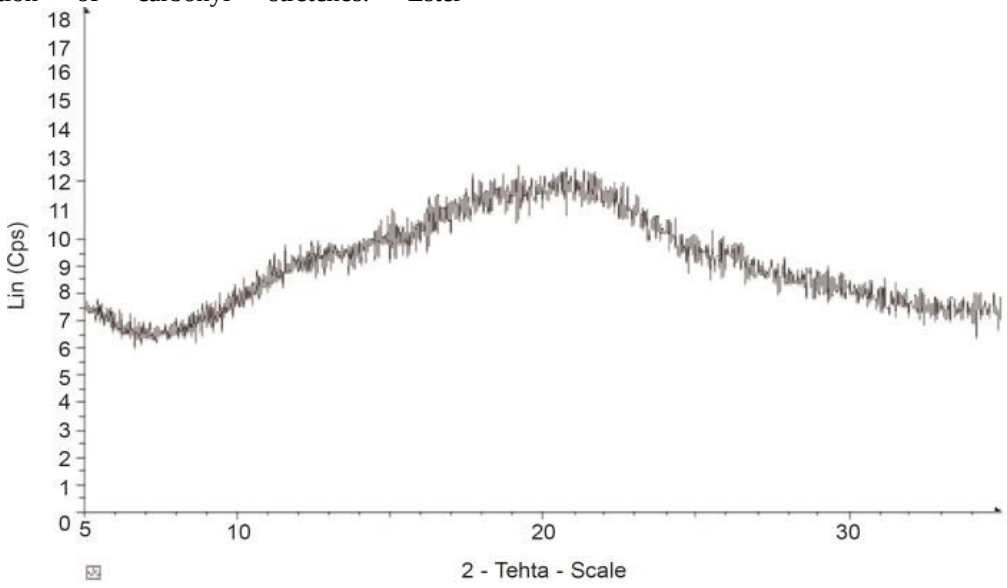

Fig:2

Scanning electron Microscopy: According to SEM analysis, okra mucilage is suitable for use as thickeners and viscosity enhancers because it is amorphous, has rough, uneven surfaces, and has a dense polymeric network structure. By considering the mucilage's rheological behaviour and physical structure, SEM's morphological insights help optimise its extraction and customisation for industrial and pharmaceutical applications(17).

Swelling index:A 10 mL graduated cylinder containing 0.1 g of okra mucilage biopolymer was transferred. Ionised water was added after the initial volume of the dried sample was measured, creating a final volume of 10 mL. A thick gel formed when the mucilage polymer swelled. The amount of swollen mucilage was assessed after a 24-hour period(18).

$$SI=\frac{Vf}{Vb}$$

Solubility: To investigate the solubility of the dry okra mucilage biopolymer in water, 0.1 g was placed in a graduated 10-milliliter cylinder. After adding deionised water to bring the amount up to 10 mL, the sample solutions were left for six hours. In addition, magnetic stirring was applied to the distributed samples for one hour at 60 °C. Following that, the sample solution was centrifuged for 30 minutes at 4000 rpm. The insoluble matrix was removed following centrifugation and dried at 105 °C until its weight remained constant(19).

$$s=\frac{w1-w2}{w1}\times 100$$

Moisture Content: This was done following the okro sample's sun-drying process. After the material had dried, 1 g was weighed. Following weight measurement, the sample was dried at 105°C in a hot air oven. At regular intervals, the weight was recorded. This went on until a steady weigher was noticed. The following formula was used to determine the moisture content percentage:

$$\text{Moisture content}=\frac{\text{initial weight} - \text{final weight}}{\text{initial weight}}\times 100$$

After being ground up and sieved, the okra sample was put in an airtight container to be utilised as an EOR fluid(20).

Swelling power: In a centrifuge tube, 180 ml of distilled water and 2 g of dry basis sample were

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heated for 30 minutes at 50–90°C with 10-degree intervals in a water bath. The suspension was centrifuged for 15 minutes at 2200 rpm after heating. After the residue was removed by suction and dried in an oven at 120°C for four hours, the weight of the precipitated paste that was removed from the sample was determined(21). The formula is as follows:

$$\text{Swelling power}=\frac{\text{weight of precipitated paste}}{\text{weight of sample}-\text{weight of residue}}$$

Physicochemical and Rheological properties:

Swelling: The primary cause of okra mucilage's swelling is its high concentration of hydrophilic polysaccharides, which allow it to efficiently absorb and hold onto water. These include galactose, rhamnose, and galacturonic acid. The okra mucilage's polymer chains hydrate and expand when submerged in water, causing the mucilage to swell and solidify into viscous gels. A number of variables, including pH, ionic strength, and the mucilage's molecular makeup, affect this swelling behaviour. Since ionisation of carboxyl groups increases water uptake, okra mucilage usually shows its highest viscosity and gelation at neutral to alkaline ph. Okra mucilage is a useful hydrophilic matrix for controlled drug release in pharmaceutical applications because it may create a swelling gel barrier that regulates drug diffusion. Its swelling capability also affects its mucoadhesive qualities, increasing its adhesion to mucosal surfaces and extending the duration of drug residence. In general, one of the most important functional properties of okra mucilage is its capacity to swell, which makes it possible to employ it as a natural polymer in food, medication delivery systems, and other industrial uses(22).

Viscosity: The shear-thinning behaviour of okra mucilage, in which viscosity decreases as shear rate increases, is one of its notable viscosity properties. A larger polysaccharide content results in a denser, more viscous substance with more molecular cross-linking, as studies have shown that the shear viscosity of okra mucilage increases with concentration. For example, an okra mucilage solution at 1% has higher viscosity values than a solution at lower concentrations.Okra mucilage is known for its strong gel-like and sticky qualities because of its much higher extensional viscosity, which is often two to three orders of magnitude higher than its shear viscosity. Temperature has an effect on viscosity as well; although less significantly, viscosity somewhat reduces with increasing temperature. Okra mucilage can be used as thickening agents, gel formers, and viscosity enhancers in food and pharmaceutical formulations due to its rheological properties, which include pseudoplasticity and viscoelasticity(23).

Film forming: Okra mucilage is a strong natural polymer that works well for making edible and biodegradable films. Its main polysaccharides—galactose, galacturonic acid, and rhamnose—form a dense network as the mucilage dries, resulting in films that are stable, flexible, and even in texture. These films are good for packaging because they block gas and moisture well, thanks to their moderate solubility and low water vapor permeability. Mixing okra mucilage with other biopolymers like starch can make the films even stronger and more heat-resistant.(24).SEM analysis shows that okra mucilage films have compact, smooth surfaces without visible defects, which reflects their strong physical integrity. Plasticisers like glycerol are often added to make these films less brittle and more flexible. Because okra mucilage films are non-toxic, biocompatible, and biodegradable, researchers are exploring their use in controlled drug delivery, cosmetics, and eco-friendly food packaging. These uses also help reduce plastic waste and support renewable resources.(25).

Thickening agent: When cellulose and uronic acid-containing polysaccharides in okra mucilage are broken down with acid, they produce l-arabinose, d-galactose, l-rhamnose, d-galacturonic acid, and d-glucose. The mucilage from L. sativum seed coats is known for its thickening and gelling properties.(26).

PHARMACEUTICAL APPLICATIONS:

Binder: Okra is a natural binding agent that can improve hardness, friability, and dissolution rate. The excess use of okra as a binder may slow down the dissolving rate of weakly soluble drugs, making okra a good candidate for prolonged release. Okra preparations can also be used as an alternative to starch in low concentrations. Okra is used in drug delivery due to its swelling and rate-retardant properties, despite being hydrophilic. Okra can be used in sustained-release formulations and can provide zero-order kinetics(27).

Disintegrant: Okra can be used as a disintegrant as it has natural polysaccharides that can absorb water and swell. It may have an effect on the crushing strength of tablets. Their physicochemical properties, such as increasing disintegrant concentration, may increase the hardness of the tablet, and also may decrease hardness in some cases(28).

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Sustained -release polymer:Acetone, an organic solvent, was utilised to extract the mucilage from Abelmoschus esculentus. To determine if the extracted mucilage was suitable as an excipient in the production of a tablet, it was subjected to a number of physiological tests. Okra mucilage was used as a sustained-release matrix excipient in varying amounts to create Lamivudine sustained-release tablets. Studies on in vitro release revealed that when the concentration of mucilage increases, the rate of release reduces. The release kinetics showed that the drug release from the matrix tablets followed non-Fickian or anomalous release because it depended on drug diffusion and polymer relaxation. The medication and the excipients utilised in the matrix tablet formulation did not appear to be incompatible.In terms of sustaining Lamivudine's release activity from the matrix, the okra mucilage demonstrated encouraging outcomes(29).

Buccal films: Due to its muco-adhesion, film-forming, and controlled-release qualities, okra mucilage is utilised in buccal films. Its high adhesion to the buccal mucosa extends the duration of interaction between the medication and the site of absorption. Its capacity to conceal an unpleasant medicine taste enhances patient compliance, and its biocompatibility guarantees safe mucosal interaction(30).

Microspheres: For a sustained release of oxcarbazepine, alginate/okra pod mucilage microspheres filled with the drug were created using the inotropic gelation procedure. The average particle diameters of these microspheres ranged from 496 μm ± 0.41 to 692 μm ± 0.22, and their drug encapsulating effectiveness was determined to be between 76.22 ± 0.01% and 90.57 ± 0.02%. These microspheres were described using SEM, FTIR, DSC, and swelling capacity analysis. These microspheres' in vitro drug release followed a sustained release (Korsenmeyer-Peppas model) pattern (R2 = 0.9552–0.9906), and the value of n > 1 indicated that the drug was released by anomalous (non-Fiskian) diffusion. In vivo experiments revealed that when oxcarbazepine was prepared as polymeric microspheres, the pharmacokinetic characteristics (Cmax, t½, AUC0-∞, Ke) differed significantly from the pure drug ($p < 0.001$)(31).

Mucoadhesive: The polysaccharides in okra mucilage work with mucosal surfaces to create hydrogen bonds and electrostatic interactions, improving bio-adhesion and resistance times for different formulations. Because it is natural, non-toxic, and biocompatible, the muco-adhesion property also strengthens therapeutic efficacy(32).

BIOMEDICAL AND FUNCTIONAL ROLES:

Biodegradability: The okra mucilage contains polysaccharides that are naturally broken down in environment by microorganisms without leaving toxic residues. For this reason, okra mucilage is often explored as a raw material in biological, agricultural, and packaging applications. Okra mucilage has been used in making films, hydrogels, packaging etc(33).

Non -toxicity comparison

Okra mucilage:Okra mucilage is safe for tissues both in laboratory and living settings. It is naturally broken down by microbes and does not leave any residue.

Synthetic polymers:Ethyl cellulose, Carbopol, and HPMC are synthetic excipients that can cause inflammation, cytotoxicity, or allergic reactions. Certain synthetic polymers might also release harmful additives or monomers, which can pose health risks(34).

Biocompatibility comparison:

Okra mucilage:It is used in formulations that require prolonged interaction with human tissues, such as medication delivery systems, bio-adhesive films, and gels, due to its strong biocompatibility with skin, mucosal, and interior tissues.

Synthetic polymers:Even though many synthetic polymers are made to be biocompatible, others are less appropriate for delicate applications or long-term use because of their foreign chemical structure, immunogenicity risk, or tissue accumulation(35).

Antioxidant: Polysaccharides and phenolic compounds found in okra mucilage have antioxidant qualities. After that, it gathers free radicals and shields the biological system from oxidative damage. It also inhibits lipid peroxidation and has a high reduction power(36).

Antimicrobial: Okra's bioactive phytochemicals have the ability to combat a variety of bacterial strains, including Klebsiella species and Escherichia coli. Gram-positive and -negative bacteria are also inhibited by it. Okra extracts were also found to have minimum inhibitory concentrations (MIC) of about 30 mg/ml for bacterial inhibition. All of this indicates encouraging antimicrobial activity(37)**.**

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Anti- ulcer:mucilage of okra is effective against bacterial pathogens like Klebsiella and Escherichia coli.The naturally present polysaccharides, flavonoids,phenolic compounds interfere important enzyme of bacterial cell membrane.it can also act against both gram positive and negative bacterial. Okra extracts can inhibit bacterial growth at low concentrations 30mg/ml(38).

FOOD AND NONPHARMA USES:

Edible packaging films:okra mucilage creates strong, pliable, and moisture retaining films that can be used as edible covering of many products like food, meats, etc. They are studied to be used as an alternative, cost effective, and regulatory approved for commercial use. Mucilage when combined with other natural polymer, nano particles enhance its tensile strength, flexibility and other activities(39).

Barrier properties: okra mucilage can act as a barrier in edible films, by reducing the transfer of oxygen & water vapour. Films derived from such mucilage containing polysaccharide reduces oxygen permeability (up to 39%less than that of CMC) which then increases shelf life and protects product from oxidative deterioration.

Water vapour permeability is also reduced up to 32% when it is added to bio-composite films as to oppose pure CMC films. Surface hydrophobicity is up to 24%which hence decreases moisture transport.

The oxygen and water vapour molecules cannot diffuse through the film due to intense hydrogen bonding inside film matrix which gives barrier effect. The mucilage also increases mechanical & thermal stability(40).

Environmental sustainability and potential to replace synthetic polymers: In comparison to the production of petroleum-based polymers, okra mucilage is a renewable crop that is easy to grow, completely biodegradable, and decomposes. Films and products made from it are non-toxic, safe for human consumption, and edible. In comparison to the production of petroleum-based polymers, okra mucilage is a renewable crop that is easy to grow, completely biodegradable, and decomposes. Films and products made from it are non-toxic, safe for human consumption, and edible(41).

Using okra mucilage instead of synthetic polymers reduces plastic pollution, reduces dependency on fossil- fuel based products. It can be recycled and reused. They can also be used as a component in bioplastics, soil stabilizers, drug delivery, coatings, sustainable hydrogels etc.

Feature	Okra Mucilage	Synthetic Polymer
Source	Natural, renewable	Petrochemical-derived
Biodegradability	Complete, rapid	Slow/non-biodegradable
Toxicity	Non-toxic, edible	Potentially harmful
Cost	Low	Moderate to high
Carbon Footprint	Low	High
Environmental Impact	Minimal	High

TABLE NO :1

Formulation Studies and Drug release profiles:

Tablet Hardness: Higher the concentration of okra mucilage harder was the tablet. The tablet showed hardness between 6.5 and 8.75kg/cm² indicating better binding capacity.

Friability: Okra mucilage-based tablets have friability less than 1% and shows good resistance to mechanical stress. The mucilage meets official Pharmacopeia requirements. Increase in amount of mucilage, decreases friability improving cohesion.

Disintegration time: Disintegration time increases with concentration, as mucilage creates a sticky gel layer that slows pill breakage. The time may vary from 5-15 minutes, dependingupon formulations. For example, the use of starch decreases disintegration, which is advantageous for continuous release.

Dissolution: Okra mucilage forms a gel barrier that regulates medication release. According to dissolution experiments, it showed nearly full drug release over a long period of time, up to 24 hours(42).

Influence of polymer concentration on drug release kinetics:

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When okra mucilage is used at low concentrations, the drug is released quickly or almost immediately. This happens because the thin gel layer lets the drug move easily into the surrounding liquid.

At higher concentrations, okra mucilage creates a thicker and stickier gel. This makes the matrix swell more, increases the distance the drug must travel, reduces its ability to move, and slows down the rate at which the liquid is absorbed.

Due to these effects at higher concentrations, the drug is released more slowly, resulting in a controlled or steady release. In tablets or microspheres, this slower release can last up to 24 hours.

Higher concentrations of okra mucilage follow non-Fickian kinetics, which is due to a combination of drug diffusion and polymer relaxation, and sustained release mostly follows zero-order, Higuchi, and Korsmeyer-Peppas models, showing release is because of diffusion and gel swelling(43).

Patent literature:

Numerous patents document the use of okra mucilage as a drug release modifier, suspending agent, film coating agent, and in floating or gastro-retentive drug delivery systems.

Patent examples include applications for diabetes management, controlled/sustained release tablets, artificial blood fluids (drag reducing agents), and compositions for taste masking and encapsulation.

Patent filings are global: China's State Food and Drug Administration approved an okra-based patented drug for diabetic complications (Z19990040), and Brazilian patent BR102020008444A2 covers okra powder mucilage(44).

Regulatory status:

Okra mucilage is used in both traditional medicine and food preparations, as it is harmless, biodegradable and non-toxic. It is not officially included in international compendia such as the FDA inactive ingredient database, the European Pharmacopoeia, or the USP despite its applications as a binder, film coating polymer, and suspending agent in pharmaceutical research. For formal inclusion standardisation, toxicological validation and development of Pharmacopeial monographs are essential. However, ongoing research and historical safety may facilitate regulatory acceptance(45).

CHALLENGES AND FUTURE PERSPECTIVES:

Limitations in large scale extraction and processing:

Variability and source dependency: The mucilage yield and properties of okra mucilage is affected by geographic, seasonal and agronomic factors. large scale production or extraction also becomes difficult.

Extraction method challenges: Mucilage may contain impurities or variable molecular weight when extracted by conventional methods such as hot water extraction, precipitation and are also often time consuming.

Stability and Preservation: The shelf life and scalability may be affected if it is not properly managed.

Cost and Energy: More alternate eco-friendly ways should be searched to use less energy, cost etc(46).

RECOMMENDATIONS FOR FUTURE RESEARCH:

Nano-formulations: The drug loading, bioavailability, targeted and controlled release on okra mucilage-based nanocarriers (nanoparticles, nanogels, and nanofibers) can be improve by taking advantage of mucilage mucoadhesive and biocompatible qualities(47).

Polymer Combinations: To enhance mechanical strength, stability and functional performance of okra mucilage for medicinal needs, it can be combined with other biodegradable polymers like HPMC, Chitosan, alginate or even synthetic biopolymer.

Clinical and toxicological studies: To promote the use of okra mucilage the systematic clinical studies are necessary to evaluate human pharmacokinetic, toxicological and effectiveness.

Standardization and quality control: For regulatory compliance and repeatable large-scale processing Pharmacopeial monographs, reproducible characterization techniques and well-defined extraction techniques are essential.

Sustainability and Green processing: Finding eco -friendly ways to reduce production cost, validation, and thereby making it sustainable(48).

II. CONCLUSION:

Okra mucilage is a promising natural polymer that offers significant advantages for drug delivery and packaging purposes. It demonstrates excellent biocompatibility, biodegradability, and non-toxicity, along with mucilaginous

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characteristics that facilitate controlled and prolonged drug release. Its natural origin, history of safe human consumption, and antioxidant and antimicrobial properties further increase its attractiveness as a multifunctional excipient. Nonetheless,issues such as variability between batches, stability concerns, high viscosity impacting processing, and a lack of standardized extraction methods and regulatory recognition hinder its current use in industry and pharmaceuticals. It is crucial to tackle these challenges through standardized protocols, enhanced extraction techniques, and gaining regulatory approval. Anticipating the future, the potential of okra mucilage-derived polymers is bright. Developments such as nano-formulations, integration with other biodegradable polymers, and clinical assessments will broaden its application in sophisticated drug delivery mechanisms. Furthermore, eco-friendly extraction and processing methods can improve its use in edible and biodegradable packaging, in line with sustainable trends.

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