Review on Hemicellulose: Abundance, Extraction and Application

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Abstract
Hemicellulose, a key component of plant cell walls, has significant attention due to its abundant presence in biomass and its versatile applications across various industries. The present review article gives an insight to availability, extraction methods and employability of hemicellulose in diverse fields of medical and other industries. Hemicellulose is composed of xylose, arabinose, mannose and galactose. Extraction of hemicellulose was done by chemical, physical and different combined methods. Extracted hemicellulose modified by chemical treatment as esterification or enzymatic reactions resulting into enhancement of its flexibility and mechanical properties. Hemicellulose and its modified forms were widely used in pharmaceuticals, food, bio-fuel and cosmetics industries.

Keywords: Hemicellulose, Extraction, Modification, Bio-fuel

1. Introduction
Hemicellulose is a complex branched polymer found in plant cell wall along with other lignocellulose material .Unlike cellulose, which consists of a linear chain of glucose molecules, hemicellulose is a heteropolymer which composed of sugar units and its exact chemical structure can vary depending upon the plant source and the specific type of hemicellulose[1]. It contains monosaccharaides such as Glucose, xylose, mannose, galactose and arabinose. The arrangement and proportion of these sugar units can vary which gives rise to different type of hemicellulose with unique structure. Due to the unique properties like biodegradability and biocompatibility hemicellulose is used for making hydrogels. These hydrogels widely used in medicines, contact lenses, protein electrophoresis etc. [2]Hemicellulose also acts as a good bio absorbent due to its high surface area, high porosity and hydrophilic nature. This property of hemicellulose used in excellent way to remove pollutants from water and other aqueous solution. It is also used in removal of variety of pollutants, such as heavy metal dyes and organic compounds and it is an environmental friendly method alternative to traditional bio absorbent such as synthetic polymers which are non-biodegradable.

2. Types of Hemicellulose:

Table 1 Different types of hemicellulose

Type of Hemicellulose	Source
Xylan	Found in hardwood and softwood.
Glucomannan	Present in some plant tubers and seeds.
Arabinoxylan	Common in cereal grains like wheat and barley.
Galactomannan	Found in legume seeds, such as guar gum.
Mannan	Occurs in various plant materials, including palms and some seaweed.
Xyloglucan	Abundant in the cell walls of many plants, including fruits and vegetables.

3. Abundance of Hemicellulose

Hemicellulose is abundantly found in biomass and plays an important role in providing strength to the plant cell wall. Natural sources of hemicellulose are discussed as follows:

3.1 Agriculture residue: Crop residues such as corn stover, wheat straw, and rice husks are sources of hemicellulose. After harvesting grains or fruits the remaining plant material contains significant amount of hemicellulose. Utilizing these agricultural residues can not only reduce waste but also provide a renewable raw-material for various applications[3].

3.2 Wood: Trees and wood are rich in hemicellulose present within the plant cell wall and provides strength and flexibility to the plant[4]. Amount of hemicellulose is varying in different species of trees and wood like softwood contains 25-40% whereas hardwood contains 38-51%.

3.3 Non-Woody Plants: Hemicellulose can be found in non-woody plants like cotton and grasses. These plants have applications in textiles and materials industries[5].

3.4 Energy Crops: Some plants are cultivated specifically for their high hemicellulose content. They have ability to grow quickly and also accumulate hemicellulose rich biomass. Example - switch grass and miscanthus. Hemicellulose extracted from energy crops can be converted into bio-fuels and other useful products[6].

The following table represents the cellulose, hemicellulose and lignin percentages of some plants-

Table 2 Percentages of cellulose, hemicellulose and lignin in plants

Source	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Wheat Straw	33-38	26-32	17-19
Rice Straw	28-34	23-25	12-14
Corn Cob	40-45	34-35	15-18
Nut Shells	25-30	23-25	30-40
Hardwood Stem	40-55	25-35	18-25
Cotton Seed hair	80-85	5-20	0
Softwood Stem	40-50	20-25	25-30
Bamboo	49-50	18-20	22-23
Corn Stover	39-40	28	7-21
Barley straw	31-45	27-38	9-14
Switch grass	35	20-22	15-16
Miscanthus	32-40	25-27	8-10
Poplar	40-43	15-18	12-17

We need to store this biomass in such a way that it prevents from further degradation. Some common methods are used for storage of biomass like- proper drying of biomass before storage to prevent moisture which causes degradation, storing of biomass in a controlled environment with low humidity and temperature can also maintain its quality. We can also store biomass in air tight containers to prevent biomass from exposure to oxygen and pests. Once the biomass is stored it undergo in a process called pre-treatment.

4. **Extraction of hemicellulose:** Hemicellulose can be extracted by physical method or by chemical method.

4.1 Physical Extraction Method: Physical method of extraction also called hot water extraction. In this method heating of biomass with water to extract hemicellulose from other components.

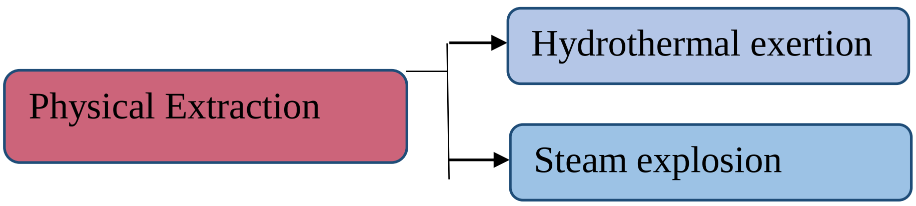

Fig.1 Physical method of extraction

a. **Hydrothermal extraction:** This process uses high temperature and water-based environment to extract hemicellulose from biomass. Hydrothermal extraction is an effective method in which heat and pressure is provided to biomass in water solution[7]. It will break down the hemicellulose from other components and will separate easily.

b. **Steam Explosion:** It is also the physical method of extraction of hemicellulose from biomass. In this biomass is treated under high pressure steam, which causes material to heat up. By heating under high pressure hemicellulose is separated from the biomass.

4.2 Chemical Extraction Method: This method is used to separate specific compounds from the mixtures by using the chemicals .In this different chemical are used which react with specific compound and helps in separation. Types of chemical extraction methods are-

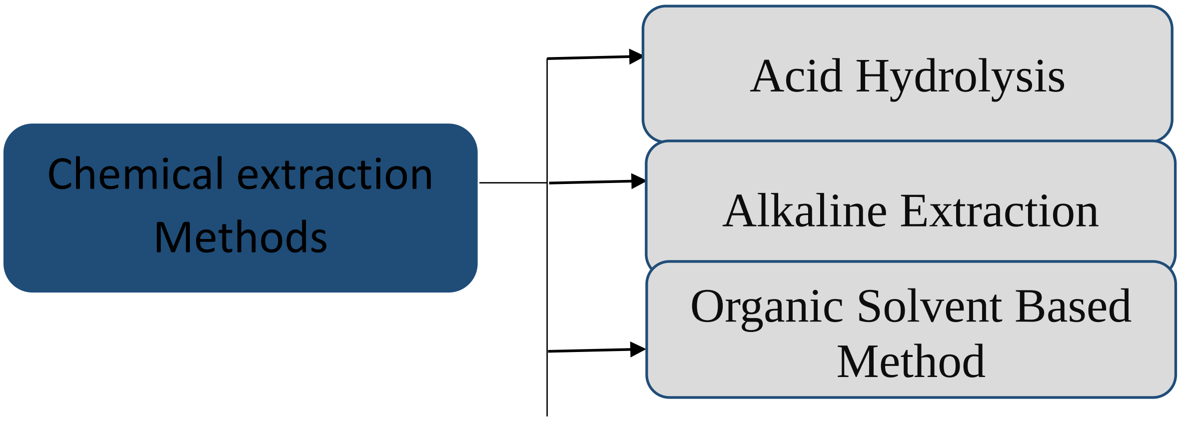

Fig.2 Chemical method of extraction

A. **Acid Hydrolysis:**

- **Process:** Acid hydrolysis involves the use of strong acids like sulphuric acid (H2SO4) or hydrochloric acid (HCl) to break down the hemicellulose molecules into smaller, soluble components[8].
- **Procedure:** The biomass was mixed with acid and heated at a particular temperature for a specific time. This broke the glycosidic linkage of hemicellulose. After heating, the solution was neutralized to adjust the pH[9]. The hemicellulose was then precipitated by adding a base like Sodium hydroxide and separated from the liquid. It was an effective method for extracting hemicellulose.
- **Application:** Commonly used in the production of bio fuels and chemicals.

B. **Alkaline Extraction:**

- **Process:** Alkaline extraction involves the use of strong alkalis like sodium hydroxide (NaOH) or potassium hydroxide (KOH) to break the ester linkages between hemicellulose and lignin, making hemicellulose soluble[10].
- **Procedure:** The biomass was mixed with alkali and heated. This alkali treatment helped solubilize the hemicellulose into the liquid phase. Once the hemicellulose was solubilized, acid was added to it to precipitate the hemicellulose[11]. The precipitated hemicellulose was then separated from the liquid.
- **Application:** Widely used in pulping processes and for hemicellulose isolation

C. **Organic Solvent-Based Methods:**

- **Process:** Organic solvent-based methods use organic solvents, such as ethanol, methanol, or acetone, to dissolve hemicellulose, while leaves cellulose and lignin behind[6].

- **Procedure:** The biomass was mixed with the organic solvent and heated the mixture under specific conditions. The solvent dissolved the hemicellulose selectively. Then solvent was evaporated to recover the hemicellulose.
- **Application:** Suitable for applications in food, biopolymers, and specialty chemicals.

4.3 Recent advances in hemicellulose extraction:

Advancement have been done in the extraction of hemicellulose which are more efficient and environment friendly

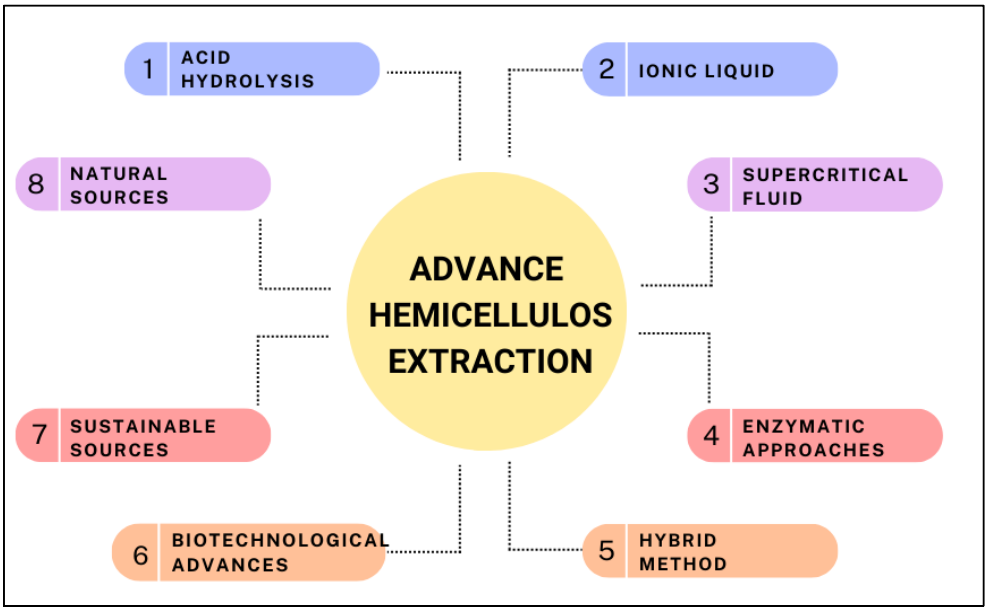

Fig.3 Advances in hemicellulose extraction

1. **Advance acid hydrolysis**

   Acid hydrolysis is commonly used method for hemicellulose extraction. Recent advancement has been done in order to improve efficiency and reduce environmental impact[12]. Researchers have developed milder acid hydrolysis conditions, using weaker acids and lower temperatures to reduce the degradation of hemicellulose and limit the formation of undesired by-products.

2. **Ionic Liquids**

   Ionic liquids are the special types of salts which can dissolve hemicellulose selectively and leave cellulose and lignin. Ionic salts like –1-ethy-3-methylimidazolium acetate and 1-butyl-3-methylimidazolium chloride shows good solubility and selectivity[13].

3. **Supercritical Fluid Extraction**

   It uses supercritical fluids like carbon dioxide to extract hemicellulose from biomass. Supercritical fluid has properties of both liquid and gas which allow it to penetrate into plant material and extract hemicellulose efficiently[14].

4. **Enzymatic Approaches**

   Xylanase enzyme breaks down the complex structure of hemicellulose into simple sugars. This method is environment friendly and used in industries for bio-fuel production.

5. Hybrid Methods

In this case, combinations of two or more methods are used. For example, combining acid hydrolysis with enzymatic hydrolysis improved hemicellulose extraction efficiency and minimize the use of acid.

6. Biotechnological Advances

Biotechnological approaches involve genetically engineering microorganisms to produce hemicellulose or modify biomass structures for hemicellulose extraction[15].

7. Sustainable Sourcing

Recent extraction techniques focus on sustainable sourcing of biomass rich in hemicellulose. This includes exploring non-food feedstock, agricultural residues, and dedicated energy crops for hemicellulose[16]. Sustainable sourcing is a continuous and environmentally friendly supply of hemicellulose-rich biomass.

8. Natural Sources

This method involves heating of biomass with steam under high pressure and then pressure was rapidly released. This causes structural changes in hemicellulose and easy to extract. It is a green and efficient method for obtaining hemicellulosic sugars.

5. Derivatization or chemical modification of hemicelluloses

Hemicellulose also has unique advantage due to presence of its hydroxyl group and various structures which are easily modified to make various things as per requirement. Some efforts was done to improve its performance which includes physical and chemical modifications-

A. **Physical Modification:** In this molecular substance was evenly distributed by blending in the hemicellulose matrix in order to increase its mechanical properties[13]. Examples- Addition of plasticizers increase film forming and film flexibility by breaking the hydrogen bond between polymer chains.

B. **Chemical Modification:** Large no. of active functional groups was added such as hydroxyl, carbonyl etc. on the main or side chain of hemicellulose increase its properties and make more suitable to use[17]. Example- Esterification reduce the tendency of hydrogen bond formation by replacing hydroxyl group with hydrophobic ester to increase its flexibility.

6. Chemical and Physical properties

6.1 Physical Properties: Hemicellulose has unique physical properties that make it distinct from other components of biomass. Because of its branching nature, this amorphous polysaccharide is soluble in water and flexible. Hemicellulose usually has a higher affinity for water than cellulose and is more hydrophilic. In addition, compared to cellulose, it has a more irregular organisation and a smaller molecular weight. Hemicellulose physical characteristics facilitate its extraction and make it a valuable material for a range of uses in the food, pharmaceutical, and bio fuel sectors.

6.2 Chemical Properties: Hemicellulose distinct qualities are a result of a variety of chemical features. Its composition varies according on the biomass source and includes different sugar units including glucose, mannose, and xylose. The sugar units in hemicellulose are joined by a variety of chemical connections, including glycosidic linkages. The individual sugar molecules can be liberated from these bonds by chemical processes like enzymatic or acid hydrolysis. Hemicellulose solubility and reactivity may be impacted by the varying degrees of branching and substitution.

7. Applications of Hemicellulose

7.1 Biofuel Production

Hemicellulose was used in biofuel production which contributes in sustainable energy solutions and reduced the use of carbon. Here, we explore the role of hemicellulose in biofuel production and its implications:

A. **Ethanol**

- **Production from Hemicellulose:** One important component of lignocellulosic biomass is hemicellulose, which is used as a useful raw material to produce ethanol. Hemicellulose was decomposed into less complex sugars such as mannose, arabinose, and xylose.
- **Fermentation:** The sugars generated from hemicellulose are then fermented to provide ethanol by microorganisms such as bacteria or yeast. This bio ethanol served as a sustainable and renewable substitute for petrol.
- **Sustainability:** Utilizing hemicellulose for ethanol production promotes sustainability by reducing the dependency on fossil fuels and diminishing the environmental impact associated with conventional gasoline[18]. It also contributes to the reduction of greenhouse gas emissions in the transportation sector.

B. **Butanol**

- **Hemicellulose:** Hemicellulose was used in butanol production which is used as an alternative biofuel with advantageous characteristics[19]. Hemicellulose-derived sugars, particularly xylose are valuable feedstock for the acetone, butanol, and ethanol (ABE) fermentation process.
- **ABE Fermentation:** In ABE fermentation, specific microorganisms like Clostridium species convert hemicellulose-derived sugars into butanol. Butanol is a versatile biofuel that can be used in place of gasoline and diesel in certain applications.
- **Higher Energy Density:** Butanol possesses a higher energy density than ethanol, making it an attractive option for industries such as in heavy-duty transportation[20].
- **Sustainability:** Like ethanol, butanol production from hemicellulose contributes to sustainability by reducing use of fossil fuels and offering a greener alternative.

C. **Biogas (Methane)**

- **Anaerobic Digestion:** Hemicellulose-rich materials such as agricultural residues and organic waste, can undergo anaerobic digestion. During this process, microorganisms break down hemicellulose and other organic matter to produce biogas, which primarily consists of methane (CH4).
- **Energy Generation:** Methane from biogas can be utilized for electricity generation, heat production, or even as a vehicle fuel. Biogas production not only generates renewable energy but also manage organic waste.

- **Waste Reduction:** Utilizing hemicellulose-rich waste materials for biogas production not only reduces the environmental impact of waste disposal but also provides an eco-friendly energy source[21].

7.2 Biopolymer and Bio composite Materials

Biopolymers and bio composite materials used as sustainable and eco-friendly alternative to petroleum-based plastics and materials. Hemicellulose is a key component of biomass, can be utilized in the development of various biopolymer-based products. Two applications in which it was used - films and coatings, and biodegradable plastics.

A. Films and Coatings: Biopolymer and bio composite materials were used in the development of sustainable films and coatings in industries. These materials are derived from renewable sources such as starch, cellulose, or proteins are eco-friendly alternative to petroleum-based films and coatings. Biopolymers possess versatile properties including barrier functions, adhesion, and flexibility which make them suitable for applications in food packaging, agriculture, and textiles. They can be used to create thin films that protect products from external factors like moisture, oxygen, and UV radiation which extends shelf life and reducing food waste. Moreover, bio composite materials which combine biopolymers with natural fibres enhance the mechanical strength and thermal stability of films and coatings[22]. By replacing petroleum-derived materials with biopolymers and bio composites industries reduce their environmental impact, minimize plastic waste, and promote a sustainable future.

B. Biodegradable Plastics: .These plastics are break down naturally through biological processes and ultimately convert into harmless substances like water, carbon dioxide, and organic matter. Starch-based biodegradable plastics widely used in disposable cutlery, packaging materials[23]. Polylactic acid (PLA), derived from renewable resources like corn-starch or sugarcane, is another popular biodegradable plastic used in various applications, including food packaging and 3D printing. Biodegradable plastics reduce plastic waste in landfills and oceans and minimize the harmful impact on environment[24].

7.3 Food and Pharmaceutical Industries

Biopolymers and bio composite materials has used in both the food and pharmaceutical industries which enhance the product quality, safety, and sustainability.

A Food industry: Hemicellulose was used in the food industry as a thickening agent, stabilizer or emulsifier in food products. It can improve texture, life and food quality.

B Pharmaceutical industry: In pharmaceutical industries hemicellulose was widely used as a binder, disintegrant or coating agent in tablet formation. It can also be used as stabilizer or suspending agent in syrups.

The following table shows all the application of hemicellulose in food and pharmaceutical industries –

Table 3 Application of hemicellulose in food and pharmaceutical industries

Application	Food Industry	Pharmaceutical Industry
Edible Films and Coatings	Extending shelf life, moisture and oxygen barriers	Controlled drug release, taste masking
Texture Modification	Creaminess and thickness was improved.	Controlled drug release, patient compliance
Emulsifiers and Stabilizers	Prevent ingredient separation in dressings, beverages	Enhanced drug formulation, improved stability
Fat and Sugar Reduction	Calorie reduction, healthier food alternatives	Reduced pill size, improved drug solubility
Packaging Materials	Biodegradable, reduced plastic waste	Sustainable packaging, reduced environmental impact
Biodegradable Utensils and Cutlery	Eco-friendly disposable products	Environmentally responsible dining solutions

7.4 Agricultural and Soil Amendments:

Biopolymers and bio composite materials plays important role in agriculture and soil management. Sustainable solutions are used to enhance crop yields, soil health, and environmental sustainability.

1. **Agricultural Applications:**

- **Biodegradable Mulches:** Biopolymers derived from starch or other natural sources, are used as biodegradable mulches in agriculture. These mulches help conserve soil moisture, suppress weed, and regulate soil temperature which ultimately enhance the crop growth and yield. They also eliminate the need for plastic mulch disposal, reducing plastic waste in agriculture[25].
- **Soil Erosion Control:** Biopolymers are used to create erosion control products such as biodegradable erosion control blankets and mats. These materials stabilize soil, prevent erosion, and facilitate vegetation.
- **Seed Coatings:** Biopolymers used seed coatings to improve seed adhesion, protect seeds from environmental stress and deliver nutrients or beneficial microorganisms to enhance germination and plant growth[26].

- **Soil Amendments:** Bio composite materials can be incorporated into the soil as organic soil amendments to improve soil structure, water retention, and nutrient availability. These amendments can enhance the fertility of degraded soils and promote sustainable agriculture.

2. **Soil Remediation**

- **Heavy Metal Remediation:** Biopolymers, in combination with natural materials or nanoparticles, was used for the remediation of soils contaminated with heavy metals. These materials bind to heavy metals protects soil and reduce environmental impact.
- **Contaminant Encapsulation:** Biopolymers can encapsulate, protect contaminants in soil and their migration which reduce the risk of groundwater contamination.
- **Biodegradable Soil Clean-up Agents:** Biopolymers was used to develop biodegradable agents for soil clean up and enhancethe bioremediation of pesticides, and other pollutants[27].

3. **Sustainable Agriculture**

- **Organic Farming:** Biopolymers and bio composite materials align with organic farming practices by providing eco-friendly alternatives to synthetic chemicals and materials.
- **Enhanced Nutrient Delivery:** Biopolymers was used to encapsulate and slowly release nutrients and fertilizers, improving nutrient use efficiency and reducing nutrient runoff.
- **Biological Pest Control:** Biopolymers can be part of integrated pest management strategies by providing substrates for beneficial microorganisms that protects the pest and diseases.
- **Waste Reduction:** Biopolymers reduce plastic waste in agriculture, especially in applications like mulching and greenhouse films.

These applications demonstrate how biopolymers and bio composite materials contribute to sustainable and environmentally responsible agricultural and soil management practices and promoting soil health, crop productivity, and reduced environmental impact.

8. Conclusion

Hemicellulose represents a valuable and versatile component of plant biomass with a wide range of extraction methods and applications. It is natural polymer plays an important role in addressing the challenges of a rapidly changing world, particularly in the sustainable resource utilization and the development of bio-based products. Further research and innovation in hemicellulose utilization are expected to contribute significantly to more sustainable and environmentally friendly future.

9. Future Prospective

The future of biopolymers and bio composite materials shows great innovation and sustainability advancements in various industries. Advanced processing techniques like nanotechnology and 3D printing expand the scope of applications for these materials. Researchers are actively working to enhance the mechanical, thermal, and barrier properties of biopolymers, making them more competitive with traditional polymers. Exploring feedstock and non-food based alternatives for extraction is important for the supply of raw material in industries. Biopolymers play an important role in functional applications such as materials with antimicrobial properties or self-healing capabilities.

Further bio plastics innovation and the development of novel materials and hybrid composites will develop more sustainable packaging and materials. In construction and automotive industries the use of bio composites in structural applications has the potential to reduce the use carbon .Moreover; biopolymers are becoming increasingly important in bio fuel and renewable energy production, contributing to a greener energy landscape.

Acknowledgement

I would like to express my sincere gratitude to all the researchers, scholars, and experts in the field who have contributed to this review article. Their valuable insights and research have greatly enriched the content and depth of this work. I would also like to thank my supervisor for their guidance and support throughout the writing process. Without their contributions, this article would not have been possible.

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