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THE FUTURE OF NANO CELLULOSE: A SUSTAINABLE NANOMATERIAL AS RENEWABLE RESOURCE

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ABSTRACT:

Nano cellulose is a versatile and sustainable nanomaterial derived from cellulose, the most abundant polymer in nature found in various plant sources. With its unique properties, nano cellulose has garnered significant attention for its potential applications across diverse fields. This material is characterized by its nanoscale dimensions, high aspect ratio, and exceptional mechanical properties, making it an ideal candidate for a wide range of advanced applications. One of the key attributes of nano cellulose is its eco-friendly nature, as it is derived from renewable resources and can be produced using environmentally friendly processes. Its biodegradability and biocompatibility further enhance its appeal for various industries, including packaging, biomedical, and environmental applications. Nano cellulose has emerged as a promising reinforcement material in composites, imparting enhanced strength, stiffness, and thermal stability to the resulting materials. This makes it particularly valuable in the development of lightweight and durable materials for industries such as automotive and aerospace. In the biomedical field, nano cellulose exhibits unique properties that make it suitable for drug delivery systems, wound healing applications, and tissue engineering. Its biocompatibility ensures minimal adverse effects, while its nanoscale dimensions enable targeted and controlled drug release. Additionally, nano cellulose-based aerogels have demonstrated exceptional absorbent properties, making them effective candidates for

environmental remediation and oil spill cleanup. The ongoing research and development in the field of nano cellulose continue to uncover new applications and refine production methods. As industries seek sustainable alternatives and innovative materials, nano cellulose stands out as a promising solution, contributing to advancements in materials science, healthcare, and environmental sustainability.

Index Words- Nano cellulose, Tissue engineering, Biodegradability, Biocompatibility

INTRODUCTION:

Nanocellulose is a versatile and sustainable nanomaterial derived from cellulose, the most abundant organic polymer found in plant cell walls. It is composed of cellulose nanofibrils or nanoparticles, exhibiting unique mechanical, optical, and rheological properties. The production of nanocellulose involves breaking down cellulose fibers into nanoscale dimensions through various methods like mechanical treatment, chemical processes, or bacterial fermentation.

Due to its exceptional characteristics, nanocellulose finds applications in a wide range of industries. In the field of materials science, it is used to enhance the mechanical strength, flexibility, and barrier properties of composites, films, and coatings. In biomedical applications, nanocellulose serves as a biocompatible material for drug delivery systems, wound healing, and tissue engineering. Additionally, its eco-friendly nature and renewable source make it an attractive alternative to conventional materials.

Nanocellulose's[1] potential extends to food packaging, electronics, and environmental remediation due to its lightweight, transparent, and sustainable attributes. As ongoing research continues to explore its diverse applications, nanocellulose stands out as a promising nanomaterial contributing to the development of innovative and sustainable solutions across various industries.

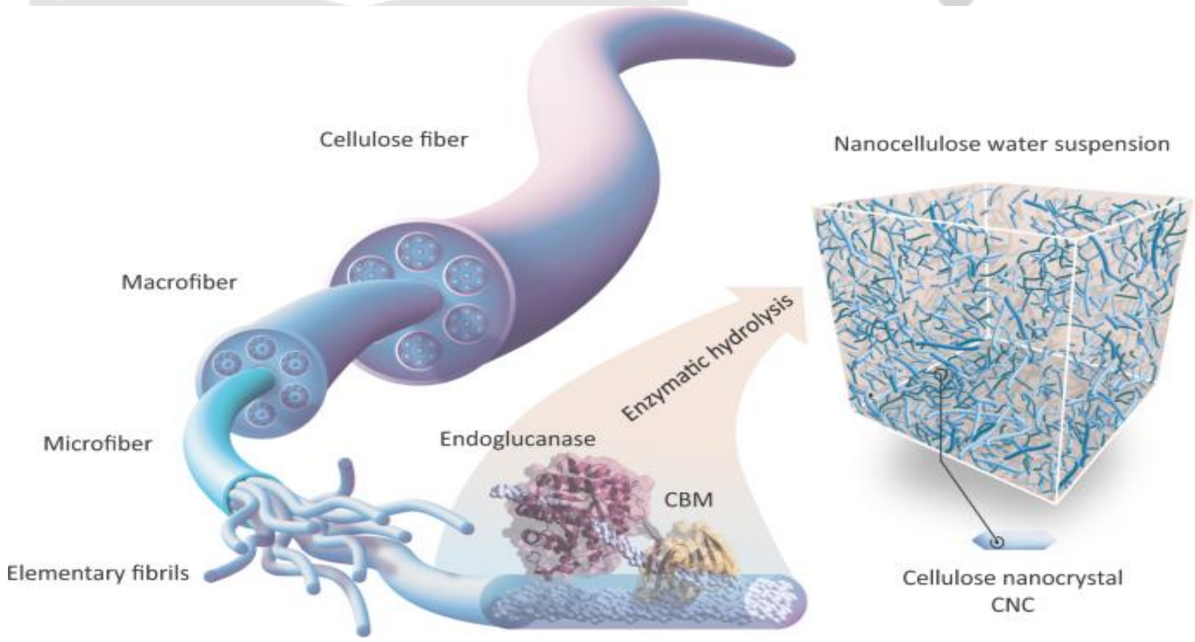

Fig.1- crystalline Nano cellulose

HISTOROLOGY-

Cellulose, a polysaccharide composed of glucose units, has a rich history dating back millions of years. Its presence in plant cell walls provides structural support and rigidity. Ancient civilizations used cellulose-rich plants like cotton and flax for textiles, dating as far back as 5000 BCE in Egypt and Mesopotamia. In the 19th century, the development of papermaking processes revolutionized communication and education. Cellulose also became a key component in industries like pharmaceuticals, food, and construction materials. As environmental concerns grew, cellulose gained attention as a renewable and biodegradable resource, driving research into sustainable manufacturing methods like cellulose-based plastics and biofuels. Today, cellulose continues to play a crucial role in various industries, with ongoing efforts to maximize its potential while minimizing environmental impact.

Nanocellulose, a versatile nanomaterial derived from cellulose fibers, has rapidly gained attention for its remarkable properties and diverse applications. Initially discovered in the late 20th century, nanocellulose research surged in the early 21st century due to its abundance, renewability, and biodegradability. It is typically produced through mechanical, chemical, or enzymatic treatments, resulting in nanofibrils or nanoparticles with high aspect ratios and large surface areas.This material has found utility across various fields including biomedicine, packaging, electronics, and environmental remediation.

Its biocompatibility makes it promising for drug delivery systems, tissue engineering, and wound healing. In packaging, it enhances barrier properties, strength, and flexibility, reducing reliance on non-biodegradable plastics. Moreover, nanocellulose-based films and coatings are being explored in electronics for their transparency and conductivity. With ongoing advancements in production techniques and applications, nanocellulose continues to be a focal point of research and innovation, offering sustainable solutions to numerous technological challenges.

Fig.2- Dr. Albin Turbuk founder of Nanocellulose

WHAT IS CELLULOSE?

Cellulose is a complex carbohydrate and the most abundant organic compound on Earth, constituting the primary structural component of plant cell walls. Composed of repeating glucose units linked together by β-1,4-glycosidic bonds, cellulose forms long, linear chains that provide strength and rigidity to plant cells. The unique arrangement of these glucose chains enables hydrogen bonding, creating a robust and crystalline structure.

In nature, cellulose plays a crucial role in maintaining the structural integrity of plant tissues, providing support and protection. Despite its abundance, cellulose is indigestible by most animals due to their inability to break the β-1,4-glycosidic bonds without the aid of specific enzymes like cellulose. Human industry has harnessed the utility of cellulose for various applications. Wood, cotton, and other plant-based fibers are rich sources of cellulose, used in the production of paper, textiles, and biofuels. Additionally, cellulose derivatives find application in pharmaceuticals, food additives, and as a thickening agent in various products.

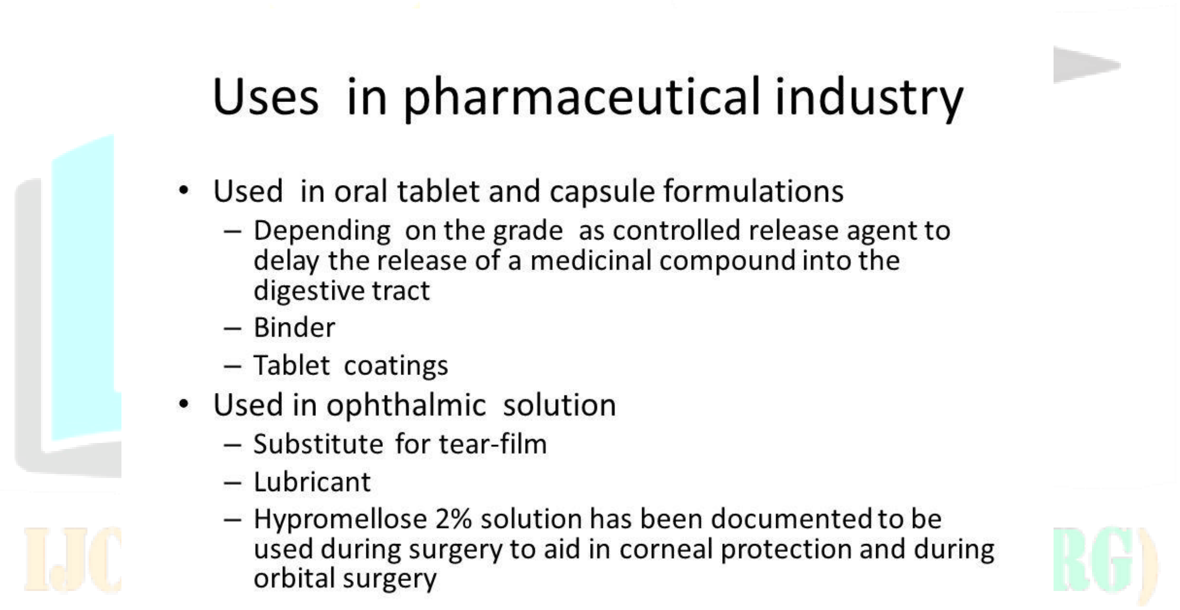

Fig.3- Various uses of cellulose in pharmacy

ADVANTAGE OF USING CELLULOSE:

Cellulose, a complex carbohydrate and the primary structural component of plant cell walls, offers a multitude of advantages across various industries and applications.

Firstly, cellulose is an abundant and renewable resource, derived from plant materials such as wood, cotton, and hemp. Its availability makes it a sustainable choice, contributing to environmentally friendly practices. Additionally, cellulose is biodegradable, reducing the environmental impact when disposed of, unlike many synthetic alternatives.

In the realm of food and pharmaceuticals, cellulose serves as a crucial ingredient in the manufacturing of dietary fiber supplements and pharmaceutical tablets. Its insoluble nature aids digestion and promotes a sense of fullness, contributing to overall health.

Cellulose is a key player in the paper and textile industries. As a papermaking material, it provides strength and durability to paper products, while in textiles, it enhances fabric strength and breathability. This versatility extends to construction materials, where cellulose-based products are used as additives in concrete and insulation, improving performance and sustainability.

Moreover, cellulose is a favored material for biofuel production due to its potential for conversion into ethanol, offering a renewable and cleaner energy source. Its use in the development of bioplastics further reduces dependency on non-renewable resources and minimizes environmental harm.

In summary, the advantages of utilizing cellulose are manifold—ranging from its renewable nature and biodegradability to its diverse applications in food, pharmaceuticals, textiles, construction, and energy. Embracing cellulose contributes to sustainable practices, fostering a greener and more eco-friendly future.

DISADVANTAGE OF USING CELLULOSE:

While cellulose offers numerous advantages, these disadvantages highlight the need for careful consideration and ongoing research to mitigate its limitations and promote sustainable and responsible use in various industries.

1. Digestibility in Humans: While cellulose serves as an essential structural component in plants, humans lack the enzymes necessary to digest it efficiently. This indigestibility can lead to limited nutritional benefits when consuming cellulose-rich foods.
2. Processing Challenges: Extracting cellulose from plant sources and converting it into usable materials can be a complex and energy-intensive process. Chemical treatments or mechanical methods are often required, impacting the environmental footprint of cellulose-based products.
3. Hygroscopic Nature: Cellulose has a tendency to absorb and retain moisture from the environment, which can affect the mechanical properties and stability of materials made from it. This hygroscopic nature may limit its applications in certain contexts, such as electronics or packaging where moisture sensitivity is a concern.
4. Limited Thermal Stability: Cellulose begins to degrade at relatively low temperatures, limiting its use in applications that require high thermal stability. This can pose challenges in certain industrial processes or when cellulose-based materials need to withstand elevated temperatures.
5. Biodegradation Rate: While cellulose is biodegradable, the rate of degradation can vary depending on environmental conditions. In some cases, cellulose decomposition may be slower than desired, contributing to issues related to waste disposal and environmental impact.
6. Land and Resource Intensity: The production of cellulose often requires significant agricultural land, water, and other resources. Large-scale cultivation for cellulose extraction may compete with

food crops or natural ecosystems, raising concerns about land use efficiency and environmental sustainability.

7. Chemical Treatment Concerns: Some cellulose derivatives used in industrial applications require chemical treatments, raising environmental and health concerns associated with the use and disposal of these chemicals. Sustainable and eco-friendly processing methods are continually being explored to address these issues.

WHAT IS NANO CELLULOSE?

Nano cellulose is a groundbreaking nanomaterial that has emerged as a versatile and sustainable solution with wide-ranging applications across diverse industries. Derived from cellulose, the main structural component of plant cell walls, nano cellulose exhibits unique properties at the nanoscale, making it a subject of intense research and development.

Fig.4- Raw Nano Cellulose

ORIGIN OF NANO CELLULOSE:

Nano cellulose originates from cellulose, a complex carbohydrate found abundantly in the cell walls of plants. The journey from conventional cellulose to nano cellulose involves innovative processing methods that reduce cellulose fibers to nanoscale dimensions, unlocking a myriad of unique properties and applications.

1. Cellulose as the Source:

   Cellulose is a fundamental structural component of plant cell walls, providing strength, rigidity, and support to plant tissues. It is composed of long chains of glucose molecules linked by β-1,4-glycosidic bonds, forming crystalline structures within the fibers. Plants, including wood, cotton, and various agricultural residues, serve as rich sources of cellulose.

2. Mechanical and Chemical Processes:

   The production of nano cellulose typically begins with the extraction of cellulose from its source material. Mechanical methods, such as high-pressure homogenization or microfluidization, physically break down cellulose fibers into nanofibrils. Chemical processes, like acid hydrolysis, selectively remove the amorphous regions of cellulose, resulting in cellulose nanocrystals. These processes are crucial for reducing cellulose to nanoscale dimensions and imparting unique characteristics to the resulting nano cellulose.

3. Bacterial Nanocellulose (BNC):

   In addition to mechanical and chemical methods, nano cellulose can also be produced through bacterial fermentation. Certain bacteria, such as Komagataeibacter xylinus, naturally synthesize cellulose during fermentation, forming a three-dimensional nanofiber network known as bacterial nanocellulose (BNC). BNC exhibits distinct properties and has applications in various fields, particularly in biomedical and materials science.

4. Types of Nano Cellulose[2]:

   The processing methods yield different types of nano cellulose, primarily cellulose nanofibrils (CNF), cellulose nanocrystals (CNC), and bacterial nanocellulose (BNC). CNF consists of fibrillar structures, CNC comprises rod-like nanoparticles, and BNC is characterized by a unique three-dimensional network of nanofibers. Each type possesses specific properties that make it suitable for various applications.

PROCESS OF CREATION OF NANO CELLULOSE[3]:

The production of nano cellulose involves breaking down cellulose fibers into nanoscale dimensions through various methods. One common procedure for making nano cellulose includes the following steps:

1. Source Material Selection: Choose a cellulose-rich source such as wood pulp, cotton, or agricultural residues.

2. Pre-Treatment: Treat the source material to remove impurities, lignin, and hemicellulose, enhancing the accessibility of cellulose fibers.

3. Mechanical Processing: Employ mechanical methods such as high-pressure homogenization or micro fluidization to physically break down cellulose fibers into nanofibrils. This process utilizes shear forces and pressure to reduce the size of cellulose particles.

4. Chemical Processing (Optional): If cellulose nanocrystals (CNC) are desired, chemical processes like acid hydrolysis can be applied to selectively remove the amorphous regions of cellulose, resulting in rod-like nanoparticles.

5. Bacterial Fermentation (Optional): Alternatively, bacterial nanocellulose (BNC) can be produced through the fermentation of cellulose-producing bacteria, such as Komagataeibacter xylinus. Purify the obtained nano cellulose to remove any residual chemicals or by-products, ensuring the material's quality. This simplified procedure outlines the essential steps in making nano cellulose, providing a foundation for various applications across industries, from materials science to biomedical research.

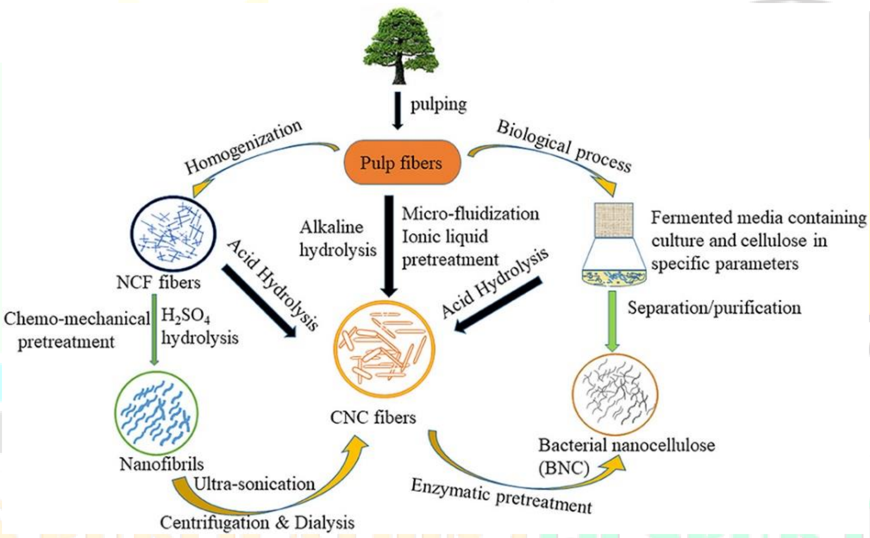

Fig.5- Synthesis of Nano Cellulose in Natural Way

TYPES OF NANO CELLULOSE:

Nano cellulose comes in various types, each possessing unique characteristics and applications. The primary types of nano cellulose include cellulose nanofibrils (CNF), cellulose nanocrystals (CNC), and bacterial nano cellulose (BNC).

- Cellulose Nanofibrils (CNF):

CNF is produced through mechanical processes that break down cellulose fibers into nanoscale fibrils. High-pressure homogenization or micro fluidization are commonly employed methods. CNF retains the fibrous structure of cellulose, creating a network of intertwined nanofibrils. This type of nano cellulose exhibits excellent mechanical properties, such as high tensile strength and flexibility, making it suitable for reinforcing materials in applications like composites, films, and coatings.

- Cellulose Nanocrystals (CNC):

CNC is obtained through chemical processes, particularly acid hydrolysis, which selectively removes the amorphous regions of cellulose fibers. This results in rod-like nanoparticles with a high aspect ratio. CNC possesses remarkable strength, stiffness, and a large surface area. These properties make CNC suitable for enhancing the mechanical and barrier properties of materials. Applications include reinforcing polymers, creating nanocomposites, and serving as a key component in advanced materials like films and coatings.

- Bacterial Nanocellulose (BNC):

BNC is unique as it is produced through bacterial fermentation, particularly by bacteria like Komagataeibacter xylinus. During fermentation, the bacteria synthesize cellulose, forming a three-dimensional nanofiber network. BNC offers a nanocellulose structure distinct from CNF and CNC. It is characterized by high purity, transparency, and an ultrafine network. BNC finds applications in biomedical fields, such as wound dressings, tissue engineering, and drug delivery, owing to its biocompatibility and unique structure.

[4]Each type of nano cellulose has its advantages and applications, allowing for a diverse range of uses across industries. Researchers continue to explore and optimize these nano cellulose types, pushing the boundaries of their applications and contributing to the development of sustainable and advanced materials.

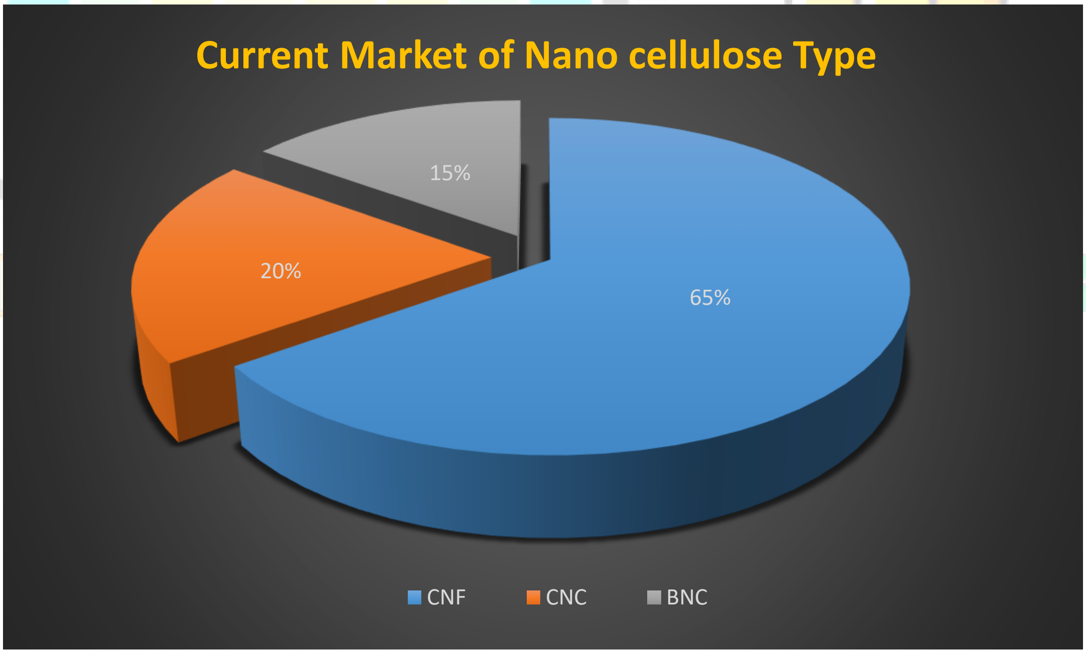

Fig.6- Types of Nano cellulose in Current Market

ADVANTAGES OF NANO CELLULOSE:

Nano cellulose, derived from cellulose fibers through mechanical or chemical processes, has gained prominence for its unique properties and versatile applications across various industries. The advantages of nano cellulose stem from its nanoscale dimensions, high surface area, biodegradability, and renewable source, contributing to advancements in materials science, biomedical engineering, and environmental sustainability.

One of the key advantages of nano cellulose lies in its exceptional mechanical properties. Despite its lightweight nature, nano cellulose exhibits high strength and stiffness, making it an ideal reinforcement material for composites. These composites find applications in industries such as automotive, aerospace, and construction, where the combination of strength and lightness is critical for performance and efficiency.

Nano cellulose's high surface area and reactivity make it an excellent candidate for functionalization and modification. This allows for the development of tailored materials with specific properties, such as enhanced water resistance, improved barrier properties, and increased compatibility with other substances. These modified nano cellulose materials find applications in packaging, where they contribute to extending the shelf life of products and reducing environmental impact through the development of sustainable, biodegradable packaging solutions.

In the biomedical field, nano cellulose has shown promise for various applications. Due to its biocompatibility and low toxicity, nano cellulose can be used in drug delivery systems, wound dressings, and tissue engineering scaffolds. Its unique properties also enable the development of transparent and flexible films suitable for biomedical sensors and wearable devices. Furthermore, nano cellulose's ability to form gels and aerogels enhances its use in drug delivery systems, providing controlled release and targeted delivery of pharmaceuticals.

Environmental sustainability is a significant advantage associated with nano cellulose. As a renewable and biodegradable material, nano cellulose contributes to the development of eco-friendly products and solutions. Its production typically involves low-energy processes, and the source material, often derived from wood pulp or agricultural residues, is renewable. This aligns with the growing demand for sustainable alternatives in response to environmental concerns and the need to reduce reliance on non-renewable resources.

Additionally, nano cellulose has demonstrated potential in energy-related applications. Its use in supercapacitors and batteries, owing to its high surface area and electrical conductivity, opens avenues for the development of efficient and environmentally friendly energy storage devices.

CURRENT MARKET OF NANO CELLULOSE[5]:

As of my last knowledge update in January 2022, the market for nano cellulose was witnessing steady growth, driven by increased awareness of sustainable and eco-friendly materials, advancements in nanotechnology, and the expanding range of applications for nano cellulose. However, it's important to note that market conditions can change, and it's advisable to check more recent sources for the latest updates on the nano cellulose market.

Nano cellulose has found applications across various industries, including:

I. Packaging: Nano cellulose is used in packaging materials to enhance their mechanical strength, barrier properties, and biodegradability. As the demand for sustainable packaging solutions grows, nano cellulose is gaining attention as a viable alternative to traditional packaging materials.
II. Paper and Pulp: In the paper and pulp industry, nano cellulose is utilized to improve paper strength, optical properties, and as a filler in paper products. This application contributes to the development of lightweight and high-performance paper products.
III. Biomedical and Pharmaceuticals: Nano cellulose has shown promise in biomedical applications, including drug delivery systems, wound dressings, and tissue engineering. Its biocompatibility and tunable properties make it an attractive material for various medical applications.
IV. Construction and Building Materials: Nano cellulose is used as a reinforcing agent in concrete and other building materials, enhancing their mechanical properties and contributing to the development of lightweight and durable construction materials.
V. Automotive and Aerospace: The automotive and aerospace industries are incorporating nano cellulose in the development of lightweight composite materials. This application helps reduce the overall weight of vehicles and aircraft, contributing to improved fuel efficiency.
VI. Energy Storage: Nano cellulose has found application in energy storage devices, such as batteries and supercapacitors, due to its high surface area and electrical conductivity. This opens up opportunities for the development of more efficient and sustainable energy storage solutions.
VII. Textiles: Nano cellulose is used in the textile industry to improve the strength and functional properties of fabrics. It contributes to the development of sustainable and eco-friendly textiles.

The nano cellulose market is expected to continue growing as research and development efforts explore new applications and the demand for sustainable and high-performance materials increases. However, market dynamics can evolve, influenced by factors such as technological advancements, regulatory developments, and shifts in consumer preferences. For the most recent and detailed information on the current market status of nano cellulose, consulting industry reports, market analyses, and news from reliable sources is recommended.

Fig.7- Global market of Nano crystalline in 2022

FUTURE OF NANO CELLULOSE IN INDIA[6]:

The future of nano cellulose holds tremendous promise, driven by ongoing research and development efforts, advancements in nanotechnology, and the increasing global focus on sustainable and eco-friendly materials. As of my last knowledge update in January 2022, the following trends and expectations shape the outlook for the future of nano cellulose:

- Expanded Applications: The versatility of nano cellulose positions it for a broader array of applications in various industries. Ongoing research is likely to uncover new uses and optimize existing applications in areas such as electronics, sensors, agriculture, and cosmetics. The ability to modify nano cellulose for specific functionalities will contribute to its adoption in diverse sectors.
- Sustainable Packaging Solutions: With a growing emphasis on sustainable practices and reduced environmental impact, nano cellulose is expected to play a pivotal role in the development of eco-friendly packaging materials. Its ability to enhance the mechanical strength and barrier properties of packaging, coupled with biodegradability, aligns well with the increasing demand for sustainable packaging alternatives.
- Biomedical Breakthroughs: Nano cellulose's biocompatibility and tunable properties make it a promising material for biomedical applications. The future may see advancements in drug delivery systems, tissue engineering, and diagnostic tools, where nano cellulose could contribute to more effective and personalized medical solutions.
- Contribution to Green Construction: In the construction industry, nano cellulose is likely to play a significant role in the development of sustainable building materials. Its use as a reinforcing agent in concrete and other construction materials can contribute to lightweight yet durable structures, aligning with the construction sector's increasing focus on green and energy-efficient solutions.
- Enhanced Energy Storage Devices: As energy storage technologies continue to evolve, nano cellulose's properties, such as high surface area and electrical conductivity, may lead to advancements in batteries and supercapacitors. This could result in more efficient and environmentally friendly energy storage solutions for applications ranging from portable electronics to electric vehicles.
- Collaborations and Investments: The future of nano cellulose is likely to be shaped by increased collaboration between researchers, industry players, and government institutions. Investments in research and development, coupled with strategic.
- Regulatory Considerations: As the use of nano materials becomes more prevalent, regulatory frameworks governing their production, use, and disposal may evolve. Future developments in regulations and standards will influence the adoption and commercialization of nano cellulose-based products, ensuring their safety and environmental compatibility.
- Global Sustainability Goals: Nano cellulose aligns with global sustainability goals, such as those outlined in the United Nations' Sustainable Development Goals (SDGs). Its renewable source,

biodegradability, and potential to contribute to various eco-friendly solutions position it as a material that can address pressing environmental challenges.

In conclusion, the future of nano cellulose is marked by a trajectory towards increased adoption, innovation, and integration into diverse industries. As research progresses and awareness of sustainable practices grows, nano cellulose is poised to be a key player in shaping a more sustainable and technologically advanced future. Ongoing developments in materials science and nanotechnology will likely unveil new opportunities and propel nano cellulose to the forefront of innovative solutions.

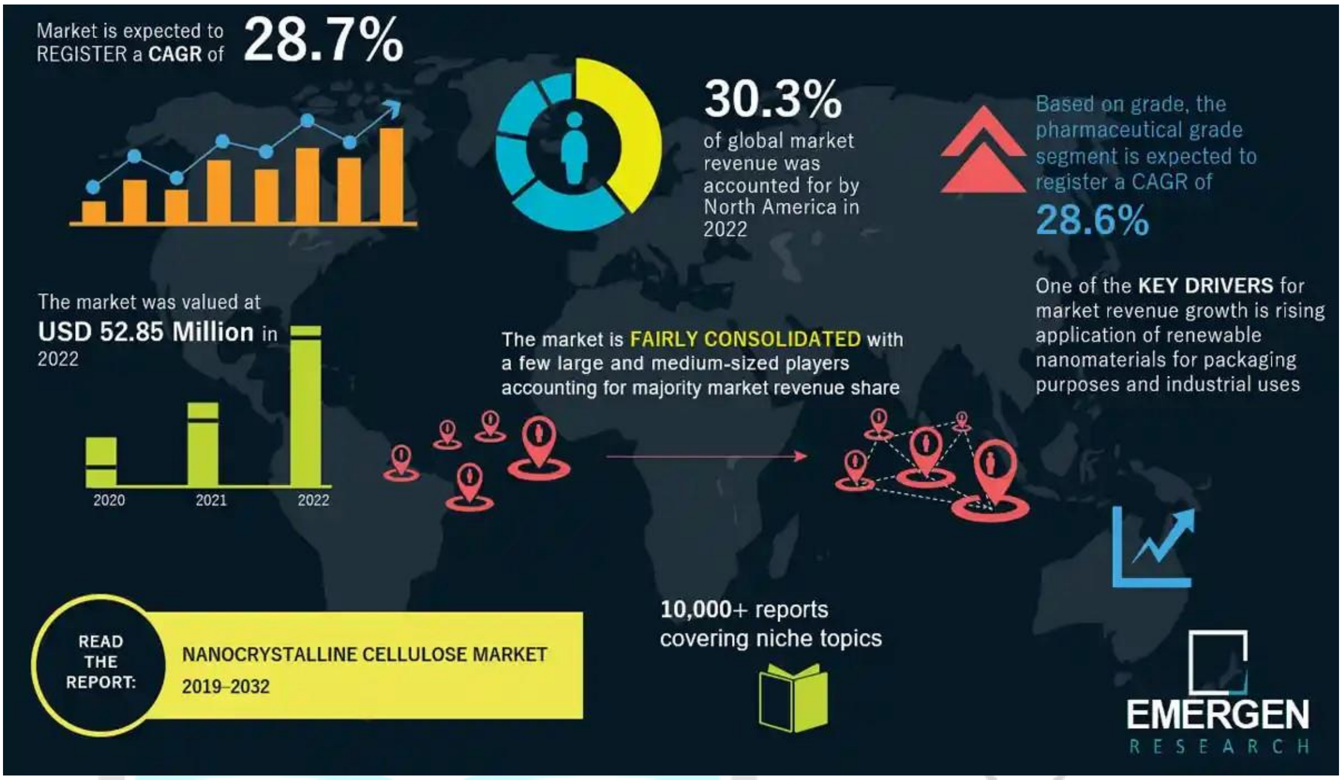

Fig.8- Nano crystalline cellulose market

CONCLUSION:

Nano cellulose, a material derived from cellulose fibers with dimensions in the nanometer scale, has emerged as a promising avenue for various applications due to its exceptional properties and eco-friendly nature. Its unique characteristics, including high surface area, high strength-to-weight ratio, biodegradability, and renewability, make it a versatile material with wide-ranging potential across multiple industries. In the field of materials science, nano cellulose offers significant advancements. Its remarkable mechanical properties, such as high tensile strength and modulus, make it suitable for reinforcing polymers and creating lightweight composites. These composites find applications in automotive components, aerospace structures, packaging materials, and biomedical devices, where the demand for lightweight, strong, and sustainable materials is high. Moreover, nano cellulose exhibits excellent barrier properties against gases and liquids, making it an attractive candidate for use in coatings, films, and membranes. These applications extend to food packaging, where nano cellulose-based materials can prolong the shelf life of perishable products and reduce food waste. In biomedical applications, nano cellulose shows promise in tissue engineering, drug delivery systems, wound healing, and as a scaffold for regenerative medicine. Its biocompatibility, tunable surface chemistry, and ability to mimic the extracellular matrix make it an ideal candidate for these applications, offering potential solutions to pressing healthcare challenges. Furthermore, nano cellulose contributes to sustainability efforts by providing an alternative to petroleum-based materials. Its renewable source and biodegradability address environmental concerns associated with conventional materials, aligning with the growing emphasis on eco-friendly practices. In conclusion, nano cellulose holds immense potential across various sectors, offering solutions to diverse challenges while promoting sustainability. Continued research and development in this field are crucial to unlocking its full capabilities and realizing its widespread commercialization.

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