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REVIEW

Overview of Nanocellulose and its Applications: Insights using Scientometric Analysis

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This overview explores the versatility and applications of nanocellulose in various technologies, including energy production, biosensors and bioelectronics. It highlights the potential of bioelectronic decals for physiological and health monitoring as well as for the fabrication of flexible light-emitting sheets. Nanocellulose is also crucial in energy storage materials, particularly in solar heat-harvesting technologies and is essential for environmental sustainability because of its catalytic use in water and air purification. The growing need for nanocellulose based sensors in the healthcare and pollution control sectors is emphasized. Furthermore, the study discusses the role of nanocellulose in 3D bioprinting and tissue engineering with the development of printable hydrogels and regenerative medicine. Furthermore, a scientometric analysis based on Scopus data from 2015 to 2024 is conducted to evaluate the research trends in nanocellulose and its applications. The study provides insights into year-wise production, the top 10 contributing authors, their affiliations, leading countries and the most influential journals in the field. By analyzing publication trends and citation metrics, this review offers a comprehensive overview of the research landscape and the evolving impact of nanocellulose in scientific and industrial applications. Nanocellulose is a revolutionary and promising material with immense potential across multiple domains.

Keywords: Nanocellulose, 3D bioprinting, Tissue engineering, Thermal conductivity.

INTRODUCTION

A substance obtained from natural resource of cellulose of nanometric size is called nanocellulose. The primary source of extraction is cellulose, which serves as the structural backbone of plant cell walls [1]. A "nanomaterial" is any naturally occurring, inadvertently occurring or constructed material that contains particles in an unbound state, as an aggregation or as an agglomeration and where one or more of the exterior dimensions of 50% or more of the particles in the numerical size distribution are in the range between 1 and 100 nm.

Nanofibrillated cellulose (NFC) is produced through the mechanical disintegration of cellulose fibers, resulting in the nanoscale fibrils characterized by a high surface area, flexibility and aspect ratio. Bacterial cellulose (BC), also referred to as nanocrystalline cellulose (NCC) in some contexts, is biosynthesized by specific strains of bacteria. This process yields cellulose with exceptional purity and a highly crystalline nanostructure. BC exhibits remarkable mechanical strength, high aspect ratio, large surface area, biodegradability, renewability and biocompatibility. Owing to these superior physico-chemical and biological properties, both NFC and BC are considered versatile, sustainable and eco-friendly materials suitable for a wide range of advanced applications [2-8].

Nanocellulose has gained significant attention in recent years due to its special qualities and potential applications in various industries. The history of nanocellulose may be traced back to the early 1980s, when researchers first began to investigate the separation and characterization of cellulose nanocrystals (CNCs) and cellulose nanofibrils (CNFs) [2,9]. Throughout the 2000s and 2010s, there was a surge in research focused on the properties and potential applications of nanocellulose,

leading to a better understanding of its unique mechanical, optical and rheological properties [7,8]. In recent years, the focus has shifted towards the commercialization and industrial scale production of nanocellulose for various applications, including composites, packaging, biomedical devices and more [10-12].

Fundamental features of nanocellulose: Many features of a material change as it moves from the microscale, where cellulosic fibers are found, to the nanoscale, where cellulose nanoparticles are found. These changes are anticipated to lead to the development of new potential uses. The subsequent section summarizes the principal physico-chemical properties affected by the transition to the nanoscale regime [13-15].

Particular surface area: Reducing a material's size results in an increase in its specific surface area or total surface area per unit of mass. Because of the irreversible aggregation of nanoparticles after drying, the particular area of surface determined by the gas adsorption isotherm is typically incorrect. The mean geometrical dimensions of nanoparticle and a rod-shaped geometry can be used to approximate the density of crystalline cellulose, which is typically 1.5 or 1.6 g cm^{-3}. The CNF and CNC values obtained from sisal fibers were 51 and 533 m^2 g^{-1}, respectively. An extreme rise is observed when the diameter falls below 20 nm, which is the diameter range of the CNC. Aerogels can be manufactured and used as porous templates for many nano-applications due to their huge specific surface area and low suspension concentration. To modify the aerogel network's wetting properties for nonpolar liquids and oils, chemical changes can be implemented. Moreover, it can be impregnated with different precursors that yield functional nanoparticles along the cellulose nanofibers with ease.

Aspect ratio: The aspect ratio (length to width ratio) is an important parameter for nanocellulosic materials. The aspect ratio controls the reinforcing characteristics and anisotropic phase development. The mechanical percolation approach is an excellent method for characterizing the mechanical properties of nanomaterial-based nanocomposites created by casting or evaporation. This approach creates a strong, constant network of nanoparticles connected by hydrogen bonds, implying an astonishing and unique reinforcing effect. Furthermore, this phenomenon is expected to become obvious only above a critical filler phase volume percentage, referred as the percolation threshold, which is determined by the nanoparticle's aspect ratio. Furthermore, tensile tests on films created by drying a series of CNC suspensions in water revealed that the films tensile modulus rose as the aspect ratio of the nanoparticles increased. Dewatering films can also be used to examine the quality of microfibrilated cellulose (MFC) or cellulose fiber (CF). This enables the examination of the tensile index and the tensile energy absorption (TEA) index. However, due to the tiny particle size, CNC and CNF cannot be used in the procedure of dewatering to produce film. Identifying the length is challenging, making determining its value for CNF tricky. For fibers that have been prepared with TEMPO, it is thought to be extremely high, although it significantly drops as the oxidation strength increases. The aspect ratio for CNC is found to be more easily determined and is dependent on the hydrolysis conditions as well as the source of cellulose. For cellulose derived from cotton, the aspect ratio typically ranges from 10 to 67, whereas for cellulose obtained from tunicin or *Capim dourado* (golden grass), the aspect ratio can reach values as high as 100 [13].

Mechanical properties: Tensile characteristics of the nanocomposites strengthened by 1, 3, 5 and 7 wt.% loading of nanocellulose. At 1 wt.%, the tensile modulus lowers; it then rises to 5 wt.%, levels out and then repeats this procedure. The nanocomposite's tensile modulus rises to 60% at a 5 wt.% nanocellulose concentration. The tensile strength and tensile modulus of the nanocomposites showed a similar pattern. At 5 wt.% nanocellulose content, there is a 28% increase in strength. The mechanical characteristics of the nanocomposite were negatively impacted by the addition of 1 wt.% of nanocellulose. The failure strain difference between the matrix and nanocellulose can help to explain this. In other words, when the matrix polymer has a much higher failure strain than the nanocellulose, the nanocellulose provides little to no reinforcement. As a result, the nanocomposite fails before the stress from the matrix reaches the nanocellulose. As previously mentioned, the modulus and tensile strength of the nanocomposites may decrease due to the potential aggregation of nanocellulose at a loading of 7 wt.%. In other words, at this concentration, the nanocellulose was not uniformly dispersed within the polymer matrix [16].

To evaluate the improvement in the properties of PVA following reinforcement with nanocellulose particles, the mechanical properties of the resulting composite films were measured. The tests were performed according to ASTM D 882-92 standards (ASTM 2012). From the films, strips measuring 60 mm by 13 mm were cut from rectangular samples. Before measuring mechanical characteristics, the cut films were conditioned at temperatures and relative humidity of 23 ± 2 ºC and 50 ± 10%, respectively. Eqns. 1 and 2 are used to determine the tensile strength and elongation at the break of the films, respectively, three measurements were taken and the stated figure was the mean with standard deviation [17].

$$\text{Tensile strength} = \frac{\text{Maximum breaking load applied}}{\text{Cross sectional area of the film}} \quad (1)$$

$$\text{Elongation at break} = \frac{\text{Final length at break} - \text{Initial length}}{\text{Initial length}} \quad (2)$$

The enhanced mechanical capabilities of nanocellulose hydrogels *via* twofold crosslinking were the most remarkable aspect of this work. The hydrogel of chemically cross-linked nanocellulose was flexible, yet it gave the hydrogel considerable toughness. Physical cross-linking increased the strength nanocellulose hydrogel of at simultaneously. Regarding strength and toughness, double-crosslinked nanocellulose hydrogels are superior than singly cross-linked hydrogels when viewed from a macro perspective [18].

Thermal stability: While determining the possible applications of nanocomposites in various sectors, such as the biochemical and packaging industries. Researchers create high-performing polymers with greater heat stability by examining the degradation behaviour of nanocellulose to improve the design and manufacturing conditions of nanocomposites. Comprehending the thermal behaviour of nanocellulose during the extrusion and compounding of nanocellulose and thermoplastic composites is also crucial. Since nanocellulose decomposes

at a temperature of between 200 and 300 ºC, it is necessary to maintain a compounding temperature of 200 ºC during the production process to avoid nanocellulose deterioration. Variations in the nanocellulose's supply, matrices used, processing methods and drying procedure may have an influence on the heat stability of nanocomposites. Thus, the purpose of this review is to examine the effect of nanocellulose addition on the thermal stability of nanocomposites [19].

Thermal conductivity: In the domains of materials science, electronics, building insulation and allied fields particularly those requiring high operating temperatures, thermal conductivity is crucial. Researchers need to have a solid grasp of thermal conductivity since it helps them choose the right materials for insulation or thermal conduction, which improves product development and design.

Understanding thermal conductivity is crucial to preventing overheating of materials used in electrical equipment. In comparison to a plain epoxy composite, the grafting of polyethylenimine onto CNF demonstrated a 35.01% improvement in heat conductivity. This may be explained by the phonon propagation of CNF, which increased the nanocomposites heat conductivity [20]. Research on heat conductivity in nanocellulose composites has not frequently focused on the effects of adding nanocellulose to the material. Thus, additional studies are needed to assess the impact of filler dispersion, processing method, filler size and aspect ratio on thermal conductivity [19].

Scientometric approach for nanocellulose and its application: For the purpose of the study data was collected from the Scopus database using the search query limited to, covering to the period from 2015 to 2024. The search was conducted using the key phrase " TITLE-ABS-KEY ("Nanocellulose" AND "Applications") AND PUBYEAR > 2015 AND PUBYEAR < 2024 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English"))." Only research articles publi-shed in English were selected for the study, resulting in a total of 3,694 articles were published and were considered for the study.

Year wise productivity: The field of nanocellulose and its application research has seen a significant increase in publications over the past decade, indicating growing interest in this area. In 2015, there were only 66 publications, whereas by in 2024, the number had surged to 862. This exponential growth highlights the expanding research focus and the increasing recognition of nanocellulose applications. However, despite this rise in publications, the mean total citations per article (MTCY) have declined over the years, from 114.32 in 2015 to 3.13 in 2024. This trend suggests that older papers have had more time to accumulate citations, whereas newer studies have not yet gained substantial recognition in the scientific community as shown in Table-1.

The mean citations per year (MTCY) also show a decreasing trend, dropping from 10.39 in 2015 to 1.56 in 2024. While this is expected due to the recency of newer publications, it may also indicate that citation distribution is becoming more diluted as the number of studies increases. Earlier studies (2015-2018) received a higher number of citations per article, signifying their foundational impact on the field. In contrast, newer studies (2022-2024) are yet to reach comparable citation levels, likely due to the time required for citations to accumulate.

TABLE-1
YEAR WISE PRODUCTIVITY OF NANOCELLULOSE BASED ARTICLES

Year	Mean TC per art	N	Mean TC per year	Citable years
2015	114.32	66	10.39	11
2016	73.91	80	7.39	10
2017	77.98	116	8.66	9
2018	73.67	202	9.21	8
2019	54.47	309	7.78	7
2020	45.49	393	7.58	6
2021	35.12	469	7.02	5
2022	19.81	549	4.95	4
2023	12.31	612	4.10	3
2024	3.13	862	1.56	2

The citable years metric further supports this observation. Older studies have had more years for citation accumulation, with papers from 2015 having 11 citable years, whereas those from 2024 have only 2 citable years. This aligns with the well-established pattern that research impact is often realized over time. However, the declining citation rate per article in recent years may also suggest a shift in research focus, increased competition among publications, or the emergence of new areas within nanocellulose and its application research that divert citations away from earlier works. These trends indicate a growing research trend interest in application of nanocellulose research, accompanied by a declining average citation impact per paper, which is a common pattern in rapidly expanding scientific fields.

Top ten authors: The bibliometric analysis of leading researchers in nanocellulose and its applications studies reveals notable trends in productivity, citation impact and research growth. Liu Y emerges as the most influential author, with the highest h-index (32), g-index (57) and total citations (3466) despite starting research in 2018 as shown in Table-2. This suggests a rapid accumulation of citations, further supported by an m-index of 4, indicating a strong research momentum. Another author, Wang Y leads in publication volume, with 107 papers, accumulating 3246 citations and an h-index of 30. This high output, combined with a relatively strong citation record, highlights Wang Y's consistent contributions. Li J (h-index 31, TC = 2902) and Li Y (h-index 27, TC = 2914) also stand out as highly cited authors, having been active since 2015.

The m-index, which measures the rate of citation accumulation, shows that Liu Y (4), Chen Y (3) and Zhang Y (2.889) have the fastest-growing impact, suggesting a more recent but highly influential research presence. Established authors such as Li J (2.818), Wang Y (2.727) and Wang Z (2.5) continue to maintain strong but steady growth in citations.

Comparing older and newer researchers, it is evident that authors who began publishing earlier (2015-2016) have accumulated higher total citations, while more recent contributors (2017-2018) are gaining rapid recognition. Other researchers, Chen Y, Li X and Liu H, who began publishing around 2017-2018, show a promising trajectory, with h-indices around 24 and relatively high citation numbers.

TABLE-2
TOP TEN RESEARCH PROFILE OF AUTHORS FOR NANOCELLULOSE BASED ARTICLES

Author	h_index	g_index	m_index	TC	NP	PY_start
Liu Y	32	57	4.000	3466	96	2018
Li J	31	52	2.818	2902	96	2015
Wang Y	30	54	2.727	3246	107	2015
Li Y	27	53	2.455	2914	84	2015
Zhang Y	26	46	2.889	2234	84	2017
Wang Z	25	52	2.500	2760	67	2016
Chen Y	24	48	3.000	2421	73	2018
Li M	24	46	2.400	2188	59	2016
Li X	24	41	2.667	1779	78	2017
Liu H	24	42	2.667	1790	52	2017

Top ten affiliations: The data indicates that research applications of nanocellulose have seen a rapid expansion in author contributions since 2015, with certain researchers maintaining dominance in citations while newer researchers are quickly establishing influence. The increasing number of high impact authors suggests a growing and competitive research landscape, with multiple contributors driving advancements in the field.

The analysis of institutional contributions in the application of nanocellulose research reveals that Nanjing Forestry University leads the field with the highest number of publications (202 articles). This indicates a strong research focus on nanocellulose and related materials. With 164 published research articles, South China University of Technology stands out for its substantial involvement in the field. Among the top contributors as shown in Table-3, Donghua University (98 articles) and Aalto University (95 articles) also demonstrate substantial research activity, likely emphasizing cellulose-based materials and their applications. Monash University (82 articles) and KTH Royal Institute of Technology (77 articles) highlight the growing global interest in nanocellulose research beyond China, with notable contributions from Australia and Sweden.

TABLE-3
TOP TEN CONTRIBUTING
INSTITUTIONS ON NANOCELLULOSE

Affiliation	Articles
Nanjing Forestry University	202
South China University of Technology	164
Donghua University	98
Aalto University	95
Monash University	82
Kth Royal Institute of Technology	77
Beijing Forestry University	73
Northeast Forestry University	72
Universiti Putra Malaysia	71
Shaanxi University of Science and Technology	64

Several forestry-focused institutions, including Beijing Forestry University (73), Northeast Forestry University (72) and Universiti Putra Malaysia (71), demonstrate that progress in forestry and biomass-based research plays a pivotal role in advancing nanocellulose technologies. Shaanxi University of Science and Technology (64 articles) also maintains a strong presence, indicating diverse research applications of nanocellulose in materials science and engineering.

Top ten contributing countries: Table-4 provides insights into the top ten productive countries around the globe in application of nanocellouse research. China leads significantly with 1,202 articles, accounting for 32.9% of the total, followed by India (6.3%) and the USA (5.5%). Despite its dominance, China has a relatively low multi-country publication (MCP) percentage of 22%, indicating a focus on domestic collaborations. Countries like Canada (51.5%), Finland (50.9%) and Sweden (46.6%) exhibit high MCP percentages, reflecting their strong emphasis on international partnerships despite lower overall output. In contrast, Korea (21.9%) has the lowest MCP percentage, suggesting a preference for local collaborations.

TABLE-4
TOP TEN CONTRIBUTING COUNTRIES
IN THE FIELD OF NANOCELLULOSE

Country	Articles	Articles (%)	SCP	MCP	MCP (%)
China	1202	32.9	938	264	22.0
India	229	6.3	174	55	24.0
USA	202	5.5	142	60	29.7
Brazil	187	5.1	130	57	30.5
Korea	146	4.0	114	32	21.9
Sweden	133	3.6	71	62	46.6
Malaysia	125	3.4	70	55	44.0
Finland	112	3.1	55	57	50.9
Japan	110	3.0	83	27	24.5
Canada	99	2.7	48	51	51.5

Top ten journals: Table-5 and Fig. 1 provides insights into the top ten preferred communication channels used to publish the research outcome of application of nanocellouse and application research. The journal 'Carbohydrate Polymers' stands out with the highest bibliometric indicators, including an h-index of 63, g-index of 90 and an impressive total citation count (TC) of 11,054 from 236 published papers since 2015, indicating its significant impact in the field. Other prominent journals include Cellulose, with a TC of 6,427 and 270 papers and ACS Applied Materials and Interfaces, which has a TC of 6,086 from 99 papers. Both demonstrate strong influence, as reflected in their h-index values of 45 and 46, respectively.

TABLE-5
LIST OF TOP TEN JOURNALS PUBLISHES NANOCELLULOSE BASED ARTICLES

Source	g_index	h_index
Carbohydrate polymers	90	63
ACS Applied Materials and Interfaces	77	46
Cellulose	65	45
ACS Sustainable Chemistry and Engineering	55	36
Chemical Engineering Journal	58	35
International Journal of Biological Macromolecules	56	35
Industrial Crops and Products	53	29
Polymers	38	26
Nanomaterials	39	25
Advanced Functional Materials	32	23

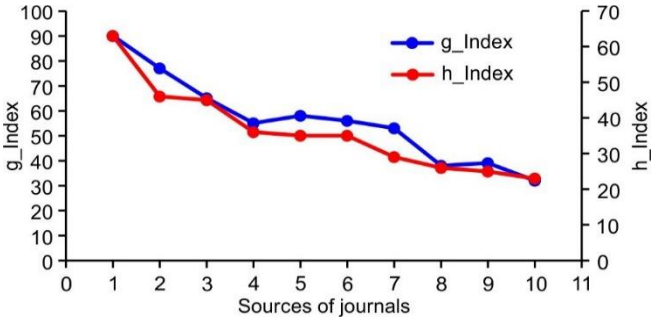

Fig. 1. Sources of journal communication

Journals like ACS Sustainable Chemistry & Engineering and Chemical Engineering Journal also exhibit notable contributions with h-indices of 36 and 35, respectively and steady growth in citations. Meanwhile, Industrial Crops and Products and Polymers contribute moderately with h-indices of 29 and 26 and publication counts of 113 and 129, respectively. The relatively newer journal Nanomaterials, starting in 2018, has already achieved a strong m-index of 3.125, demonstrating a promising trajectory. Advanced Functional Materials, though impactful with an h-index of 23, has fewer articles (32) and citations compared to the others, signifying a narrower yet focused contribution.

Applications of nanocellulose: A few factors influencing the properties of nanocellulosic materials are the age of the fibers, the source of the plant material, their chemical composition, the kind of separation used, faults in the fibers such pits and nodding and the growing environment of the plant. Due to numerous studies, mechanical, optical and gas barrier of nanocellulosic materials attributes have advanced to the point that they may be applied in a wide range of settings. The uses of nanocellulose in textiles, healthcare, electronics and gadgets, printed electronics and as substrates for metal nanoparticle catalysts are extensively covered in a number of reviews [21-23]. Current state-of-the-art improved nanocellulose features and applications are illustrated with some of the most interesting uses.

Mechanical reinforcement: With a Young's modulus of around 70 GPa at a density of roughly 2.6 g/cm^3, nanocellulose fibers are stronger and have a lower tensile modulus than glass fibers. Nanocellulose is often used in composites to try to replace glass fibers. On the other hand, Kevlar has a modulus between 60 and 125 GPa and 1.45 g/cm^3, whereas steel has a high density of 8 g/cm^3 and a modulus of 200-220 GPa. Steel only provides 25 J/g, but when specific Young's modulus, which takes density into account is employed, nanocellulose measures 65 J/g for microfibrils and 85 J/g for nanocrystals.

These days, a variety of applications usually chosen for composite materials, which are composed of a polymeric matrix with a filler material serving as reinforcement. Artificial fillers like carbon, aramid or glass fiber are typically utilized. When fillers are added to a polymeric material, the mechanical and thermal characteristics of composite material are enhanced in comparison to the polymeric material alone since fillers are so effective and adaptable. Undoubtedly, a lot of attention is being paid these days to climate change and artificial fillers used in composite materials, since they present disposal issues at the end of their useful lives because of their limited combustibility and the growing need for material reuse techniques. Natural fillers, including cellulose fibers, starch or chitin, offer several positive environmental consequences in addition to financial savings, decreased density, improved thermal properties and biodegradability. When cellulose nanocrystals and nanofibrils were compared to the empty polymer matrix, the mechanical and thermal characteristics improved similarly. The network of hydrogen bonds that binds the cellulose molecules inside the polymer matrix is most likely what gives nanocellulose fillers their strengthening action. Cellulose nanofibrils shape allowed them to perform better mechanically and thermally than the other two distinct nanocellulose fillers. The more flexible and hairy nanofibrils showed a tangling effect more than the extra specific cellulose crystals [24,25].

First, if the right dosage of nanocellulose is applied, it may be utilized to enhance the mechanical qualities of cementitious materials. It should be mentioned, nevertheless, that using a high dose of nanocellulose may cause it to aggregate, which might reduce its mechanical characteristics. CNCs obtained from the different sources and handling techniques might impact the hydration of cement when different types of cements used. Importantly, it was found that while all CNCs may increase the degree of hydration at a given age, the CNCs generated *via* transition metal-catalyzed oxidation were more effective than the CNCs generated *via* acid hydrolysis. Enhancing hydration heat release is crucial for all types of cement. These nanocelluloses have some characteristics in common, like high surface area, high strength, low density, large aspect ratio and a low density, even though their sources and methods of separation are different. In addition, nanocelluloses are highly hydrophilic, which means that when combine with cementitious materials, they can absorb some water due to their surface hydroxyl groups [26,27]. In cement, the nanocellulose materials are added to increase sound absorbing property of the cement in order to make the more ecofriendly and safer product [28,29].

Although, nanocellulose-cement matrixes are more prone to hydrophilicity of the cellulose component so they are less sturdy because of its lower chemical stability. In addition to that cellulose components lose their contact with the cement over time will form the cracks on the cement. The two methods used to prepare the composite are: (i) incorporating bacterial nanocellulose into the cement composite in gel form, and (ii) coating the cellulose fibres with bacterial nanocellulose. Depen-

ding on the method of administration of bacterial nanocellulose the surface roughness, degree of hydration, surface basicity, fiber mineralization would impact positively [30,31].

He *et al.* [32] developed a thermosetting polymer system by adding dialdehyde and microcrystalline cellulose to epoxidized soybean oil for reinforcement. The epoxidized soybean oil polymer had a well-dispersed dialdehyde cellulose. The resultant composite had excellent toughness and thermal stability because the filler and matrix interacted well [19]. The incorporation of bacterial cellulose materials in the composition of wood pulp will give a high quality paper [33]. The distinctive properties of cellulose nanocrystals, also known as microfibrillated networks (MFCs), such as their high stiffness, fibrillar shape, low density, biomass origin, abundance and impending commercialization, are generating increasing interest in them [34]. The first report on its mechanical reinforcing property came from Mohammadkazemi *et al.* [35] and He *et al.* [32]. Microcrystalline and dialdehyde cellulose were used to enhance the epoxide soybean oil. The enhancements were mostly attributed to the fillers improved dispersion and the chain entanglement-induced high interfacial adhesion between the fillers and matrix. Minor surface modifications of the CNCs can significantly enhance their mechanical properties, enabling their effective use as reinforcement in polyester-based nanocomposites [36].

Light-weight materials like hydrogels, foams and aerogels need particular CNCs for the mechanical support. For these materials, the CNCs and CNFs serve as mechanical stabilizers. The nanocellulose filler will mechanically stabilize the foams by altering their morphology [37]. Nanocellulose filler can be used as foam stabilizer by altering its surface composition, it decreases the pre size of the foam and increase the stability of the foam [38].

Barrier properties and packaging: Plastics derived from petrochemicals are most frequently used for food packaging since they are less harmful to the environment. Since hydrogen bonds of cellulose are essential for packing, filtration and particularly food packaging, it has limited permeability and may create a dense percolating network [39]. Since 2015, the nanocellulose research on packaging has abundantly increased as presented in three reviews published in 2017 [40-42]. The nanocellulosic materials [43], in these kinds of applications, nanocellulose and other nanocellulosic materials are widely employed. Oxygen permeability [44] and water vapour transmission [45] are thoroughly studied in this regard. The nanonized structure of the nanocellulose has high density so it drastically decreases the water permeability [46] and gas permeability. The coating of cellulose nanocrystals reduces the friction of plastic films while retaining the optical properties of coating [47]. Several researchers [40-42,48,49] demonstrated that MFC becomes a transparent material when densely packed, as its tightly packed fibers create minimal interstitial space, thereby reducing light scattering. However, the processing circumstances impacted the transparency of the cellulosic materials. Nogi's research team [50-52] also created cellulose based nanopapers, which were optically transparent and had a certain transmittance range.

Clay and calcium carbonate are the two examples of inorganic fillers that may be used with cellulose nanofibres to create biodegradable coatings and films. The nonbiodegradable films used in the packing can be replaced with these films [53]. These materials are used in packaging applications since they are derived from biological sources, enhance food safety and performance, and reduce environmental pollution [48].

A major requirement for food packaging is gas impermeability, which is largely achieved by NFC. However, cellulose is hydrophilic and absorbs excess water when exposed to moisture. NFCs are sufficiently impermeable, a property confirmed by research on the oxygen barrier characteristics of nanocellulosic materials [54]. Hydrophilicity clearly makes it difficult to employ nanocellulosic materials in purposes that need materials with gas and water barriers; thus, the surface is altered to render the material more resistant to water for packing. Packaging typically utilizes polymer grafting onto the surface of nanocellulose.

The researchers describe a multilayer technique for packaging systems that uses cellulosic materials. This design protects the cellulosic materials from the effects of the moisture within by separating them from the humid surroundings [55-59]. Schade *et al.* [60] patented the use of multilayer packaging demonstrating that the NFC layer is preserved between the two water-resistant plastic layers. The application of a wax coating on CNF films significantly enhances their oxygen resistance, which is retained even in conditions of high humidity. Utilizing an MFC coating, polymer films were produced and tested to provide effective barrier materials [61,62].

The packaging of food must always provide a good barrier to oxygen and water, although it is not always ideal to develop a hydrophobic film. This was accomplished by silylating the surface using 3-aminopropyl-trimethoxysilane and even at 95% relative humidity, the surface displayed the required barrier properties [63]. In contrast, the hydrophobic properties of film were enhanced and its oxygen-barrier properties were destroyed during surface modification using hexamethyldisilazane. An alternative technique entailed using 0.1-0.5% by-weight polyamide epichlorohydrin resin to crosslink hydrophilic TEMPO-oxidized nanocellulose [64]. In a humid environment, these films retained good mechanical characteristics and apparent transparency. Humidity often breaks the between molecules hydrogen bonds that hold cellulose chains together, but crosslinking was able to effectively retain the film structure. In another investigation, nanocellulose served as the crosslinker and reinforcing filler in chitosan films [65]. The interface of nanocellulose was modified to include aldehyde groups, which quickly bonded with the chitosan to crosslink the film. The tensile durability and rigidity of the film in water were improved, although at the expense of elongation at the breakpoint. Recently, Yao *et al.* [66] reported on the application of dopamine as a linker to develop CNF-montmorillonite composites. For mechanical and barrier performance, interfacial adhesion among the matrix and the reinforcement components is crucial, particularly in high-humidity environments. Dopamine acts as an effective linker between CNF and montmorillonite by binding to cellulose nanofibrils. These nanocomposites exhibit excellent gas barrier properties, even at high relative humidity levels of 95%.

Nanocellulosic materials are widely used to develop nanopapers consist of large surface areas, high strengths, transp-

arency, foldability and low coefficients of thermal expansion. Transparent films and aerogels with exceptional mechanical, optical and thermal properties may be constructed from nanocellulosic materials, as has been extensively described. Due to high degree of transparency of CNCs [67], It has been demonstrated that the composite films of nanocellulose, ZnO, carbon and dots are highly effective UV-blocking shields [67]. Zinc oxide and CNF have been added to starch-based coating compositions to produce antibacterial coatings on paper. The Gram-positive organisms and Gram-negative organisms are both susceptible to bacteriocidal activity as demonstrated by the coated sheets [68]. Low bacterial adherence is seen on both CNF and TEMPO-oxidized CNF films [69]. Bacterial adhesion was markedly increased with the addition of polyelectrolytes to TEMPO-oxidized CNF films, showing the importance of surface chemistry in augmenting or diminishing material interactions with bacteria. El-Samahy *et al.* [70] have reaffirmed the superior air-barrier and antibacterial properties of nanocellulose coatings [70]. By incorporating CNC into a carrageenan matrix, Sanchez-Garcia *et al.* [71] demonstrated an improved water barrier, yielding a unique bionanocomposite which is recommended for use in coating and food packaging applications. For short-term items such as salad cups, containers, wrappers, drinking cups and laminated films, PLA (poly lactic acid) is utilized as a food packaging polymer [72]. However, in some conditions, the PLA's gas and water vapour qualities render it inadequate for its intended function. As a result, creating PLA nanocomposites is a way to enhance their characteristics [73]. A biodegradable PLA matrix was combined with hydrophobic-modified NCF by Song *et al.* [74] to create innovative biodegradable composites. These authors stated that the PLA matrix's water vapour barrier is enhanced by the addition of NCF [74]. A novel bionanocomposite based on PLA and CNC was prepared by Huan *et al.* [75] using two electrospinning techniques. The enhanced crystallinity and ordered structure of the electrospun fibers led to improved mechanical and thermal properties in the resulting fibrous mats [75-77].

Medical applications: The mechanical characteristics, nanofibrous network and natural supply of nanocellulose make it an intriguing material for biomedical applications. All of these components are becoming increasingly important tocustomers when it comes to health care items. Consequently, nanocellulose has found uses in hydrogels, threads and scaffolds. Even though the field of biomaterial synthesis for bone engineering applications has seen a great deal of study, scientists are still searching for a material with better cell/material interactions that has both osteoconductive and osteoinductive characteristics as well as a peripheral structure more akin to the matrix outside of cells. Bacterial cellulose has gained popularity as a biopolymer and is widely used as a matrix for the manufacture of biomaterials for uses such as tissue engineering and regenerative medicine due to its high mechanical properties, bio- and cytocompatibilities and low cytotoxicity [78-80]. Several researchers [81,82] have shown the successful utilization of a nanocellulose-collagen-apatite composite linked to protein called osteogenic growth for bone regrowth.

Nanocellulose has been proposed as a tissue culture medium to promote cell development as it has been shown to be non-cytotoxic. The cytotoxicity and potential uses of hydrosoluble phosphorous acid functionalized cellulose as a tissue scaffold matrix were evaluated in a recent work by Petreus *et al.* [83]. The phosphorous acid-modified cellulose was created by reacting microcrystalline cellulose with a melted mixture of phosphorous acid and urea. Because they were harmless, the resulting water-soluble films showed good cytocompatibility when tested for cell compatibility [83]. In contrast, according to more recent research, cellulose nanocrystals have the ability to enter cells and trigger an inflammatory response, with nanofibrillated cellulose being particularly dangerous [84]. Therefore, it seems that the cytotoxicity and inflammatory response to nanocellulose are significantly influenced by its size and form. Moreover, it has been demonstrated that surface chemistry greatly influences the inflammatory response [85]. The mechanical characteristics, biocompatibility and compatibility of modified nanocellulosic materials with other biological materials like apatite and collagen make them especially relevant to bone and tissue engineering. Studies have been conducted on phosphorylated nanocellulose as a biocompatible substance intended for use as a scaffold in the regrowth of bone. Once implanted, phosphorylated cellulose promotes the precipitation of calcium phosphate, providing the material a look akin to that of bone. Fricain *et al.* [86] developed crystalline monoesters that could grow in water and withstand γ-irradiation sterilization without significant damage. In another study, collagen was covalently linked to a bacterial cellulose matrix to produce a hybrid composite for bone repair [81]. The composite, incorporating carbonate apatite and an osteogenic growth peptide, mimics the structure of bone and supports cell growth.

To prevent more serious health issues, it is important to facilitate healing after wounds since they carry a risk of infection [87]. Human stem cells have been added to nanocellulose threads to hasten the healing process [88]. A week before surgery, these threads might be made using the patient's cells to prevent an immunological response. Glutaraldehyde was applied to the threads to keep them wet. A hydrogel for wound-healing dressings is created by cross-linking calcium ions with nanofibrillated cellulose [89]. The hydrogel is nontoxic and non-inflammatory, while maintaining an optimal level of moisture to promote healing. Recently, Zander *et al.* [90] explored with hydrogels of nanocellulose crosslinked with metal cations as scaffolds for tissue engineering. Due to their combination of mechanical strength and pliability, poly(vinyl alcohol)-based nanocellulose hydrogels have been suggested for ocular applications, capable of maintaining up to 90% water content and transparency [91]. These experiments revealed that strain caused a rearrangement of the nanocellulose alignment in films made of polyvinyl alcohol–nanocellulose composites.

A dual-membrane hydrogel consisting of CNC and alginate has controlled swelling processes that provide great promise for the customized release of antibiotics [92,93]. Furthermore, CNF films have been employed for loading and release active chemicals in a controlled manner [94]. Dong *et al.* [95] suggested modifying CNCs to administer chemotherapeutic drugs with specificity. For stomach-specific medication administration, the CNC-chitosan hydrogels developed with-

out solvents have also been proposed due to their mechanical properties and pH-dependent drug delivery capabilities [96,97]. It has been proposed as a transdermal drug administration technique to create a membrane *via* polymerization by radicals of N-methacryloyl glycine within the tangled strands of bacterial cellulose [98,99]. The addition of the bacterial cellulose produced translucent membranes with superior tensile characteristics. This composite showed prolonged drug release, pH sensitivity and non-cytotoxicity [98].

Viral filtration is an essential step in both biological filtration and microbiological water quality monitoring. The only fully unmodified natural polymer filters can remove viruses as effectively as ceramic filters, cellulose acetate, cuprammonium regenerated cellulose and polyvinylidene difluoride (PVDF), which are all synthetic or semisynthetic polymers, are those based on nanocellulose [100]. Viral elimination membranes made of nanocellulose have been utilized recently. Pure highly crystalline cellulose nanofibers and cross-linked nanocellulose based articles have been shown to be effective in eliminating highly pathogenic viruses, including the human enterovirus, hepatitis A and C viruses, bovine viral diarrhea virus, Aichi virus, xenotropic rotavirus A and murine leukemia virus [101-104]. By using appropriate physical and chemical techniques, for size-exclusion nanofiltration and the formation of viral retention filter paper, the pore-size distribution of nanocellulose may be tailored. These viral filters offer vital defense against virus particles in the air. Only Junter & Lebrun [105] examined virus-retentive screens based on nanocellulose that were effective against a variety of viruses. Furthermore, CNC might be used to suppress viruses, including HIV. CNC-based systems have been identified by Zoppe *et al.* [106] as viral inhibitors (alphavirus infectivity). In addition to its use in drug administration, CNC-based biosensors have been reported for the detection of human neutrophil elastase [107]. The ability of 3D bioprinters to deposit materials in three dimensions provides a promising approach for tissue engineering and regenerative medicine through the bottom-up construction of intricate structures [108]. Using fibrillated nanocellulose, alginate and glycerin to make a printable paste, porous hydrogels have been printed [109]. The future seems promising for these printed hydrogels, even if further study is needed to enhance their mechanical qualities [110].

Sensing and biosensing (biosensors): To protect the human health and promote wellness, it is essential to identify various compounds found in the environment, including small, macro and biomolecules [86]. The global industrial rivalry is expected to intensify and advancements in pollution control, healthcare and biomedical applications will propel the market for sensors, which is expected to reach 20 billion dollars by 2020 at an annual pace of more than 10%. Sensors are increasingly being used in biological and healthcare applications. Important areas of biomedical research include chemical sensors for home use (such as cholesterol monitoring and glucose) and biocompatible materials to be utilized with implants and prosthetics [111]. In addition, sensors are used in industrial production of toxic and hazardous gases, atmospheric environmental testing and unintentional fire explosion prevention [112].

According to a recent analysis, nanocellulose-based materials have surface, colloidal and photonic qualities that make them highly desirable sensors [113]. Pure bacterial cellulose films produced from have been shown to, for example, wild type and recombinant *Komagataeibacter xylinus* have a considerable inherent piezoelectricity; as a result, these kinds of nanocellulose might be used in piezoelectric sensors [114,115]. They also have properties that biosensing finds highly attractive. Numerous uses including food safety, bioimaging, forensics, environmental monitoring, clinical/medical diagnostics, physical/mechanical sensing and labeling, are being developed for and utilizing nanocellulose. Golmohammadi *et al.* [113] conducted a thorough analysis of the customization and use of nanocellulose in biosensing technologies in a new study. The ability to seamlessly integrate biosensors and bioelectronics into or onto the human body is facilitated by ultrathin, adaptable supports that house microelectronic equipment. These substrates hold promise for the development of permanent physiological and health monitoring systems. A thin-film organic electrochemical transistor built on a thin, porous microbial nanocellulose layer has been used to generate a self-adhering bioelectronic decal that can collect, transmit and analyze a biofluid. Using CNC to crosslink soy protein is one method of producing robust films with adaptable electromechanical properties for sensing applications. The efficient vertical fluid conveyance (wicking) of analytical substances from the bottom surface to the sensor electronics above reduces the analyte time to delivery. This is made possible by the hydrophilic and porous nanocellulose as a substrate, which is very permeable to liquids and gases. When it comes to manufacture and operation, the organic electrochemical transistor decal makes things easier and nanocellulose offers the necessary mechanical and permeability qualities. A single substrate has been used to create several devices, which are readily detached from the supporting substrate and reattached to any surface by only moistening the nanocellulose sheet. A cellulose nanocrystal or polyvinylpyrrolidone combination sheet with iridescent properties was created in order to distinguish different organic solvents [116]. Nanocellulose-based organic/inorganic hybrid nanocomposites are of interest for the (bio)-sensing of different analytes such as gases, biomarkers, drugs, proteins, DNA, infections and toxic and hazardous compounds. The colloidal properties of modified nanocellulose may be used to interact with biomolecules, as most recently demonstrated by Thielemans *et al.* [117] employing albumin. The objective was to cover nanofibrillated cellulose with silver nanoparticles in order to establish a surface-enhanced resonance spectroscopy (SERS) system for identifying pesticides. The surface plasmon resonance antenna phenomenon causes the weak Raman signal to be amplified when a coinage metal is added to SERS. The 3D fiber network produced by the CNC/silver hybrids raised surface roughness, a characteristic which is known to maximize the SERS impact [118,119].

A hydrogel consisting of TEMPO-oxidized nanocellulose has been employed to support fluorescent carbon quantum dots. The hybrid material was used to observe the fluorescence quenching that happens upon the identification of laccase enzymes. The intensity of fluorescent signal was increased by the nanocellulose hydrogel matrix while the excitation and emission wavelengths remained same. The observed effect is explained by the favourable interactions between the fluoro-

phore surfaces and the hydrogel support, enabling carbon quantum dots to disperse more effectively than in the absence of nanocellulose. Moreover, C-phycocyanin, a biosensing molecule that functioned as an effective biosensor for detecting the presence of copper ions, was also immobilized using TEMPO-oxidized nanofibrillated cellulose as a substrate [120].

Electronic and engineering applications: In future, the supercapacitors as lightweight and pliable devices will be the most significant optoelectronic use of nanocellulosic materials [121]. Nanocellulose provides the stiffness that freestanding and adaptable substances need to generate high volumetric capacitance when combined with a conductive material, usually a polymer. The three most commonly used conductive polymers are polypyrrole, polyaniline and poly (ethylenedioxythiphene). Nystrom *et al.* [122] produced CNF-based electroactive composites by coating cellulose fibrils with polypyrrole. This combination was not only electroactive but also conductive, allowing for energy storage. Optimizing the polypyrrole or nanocellulose combination resulted in a material with near-ideal pseudocapacitive properties [123]. Carbon nanofibers (CNF) have been utilized recently to produce an anode for Na^+ ion batteries by using it as a precursor [124]. An indium tin oxide (ITO) layer on the cellulose, CNF has also been utilized in organic light-emitting diodes [125]. As conductive nanocellulosic sheets are lightweight and exhibit strong thermal and chemical stabilities, they hold great promise as materials for flexible electronics. For example, the amount of silver required has decreased thanks to the high-resolution 3D printing of CNC and silver into conductive rails [126]. CNCs tin oxide layers have been used in composite electronics to create flexible organic field effect transistors [127].

Further study has been done on the possibility of using metal oxide nanocellulose materials as electrical materials with thermal insulation. Thermal conductivity was reduced by an order of magnitude when a ZnO–TEMPO-oxidized nanocellulose film was produced as compared to only the ZnO film [128]. However, there was no information on the electrical characteristics of the hybrid films.

Utilizing nanopapers as models, electronic materials have been developed [129]. Using minimum porosity and dense nanocellulose packing [130], nanocellulose films outperform conventional papers coated with conductive substances in terms of conductivity. Minerals ($CaCO_3$, $Ca_x(PO_4)_y$ and montmorillonite), metals (Au, Ni, Pd and Ag) and carbon (graphene and carbon nanotubes) nanomaterials have all been employed as the host matrix on nanocellulose substrates [131,132]. For the development of translucent and flexible light-emitting sheets, the electroluminescent qualities displayed by cellulose-based systems are encouraging [133]. The optoelectronic devices can employ nanofibrillated cellulose with luminous phosphorus as the active component due to its electroluminescent capabilities when placed on a PVDF membrane covered with silver nanowire [134]. This lays the groundwork for producing practical, adaptable and transparent light-emitting sheets for commercialization [135].

Energy conservation and production: A recent research examined materials based on nanocellulose for electrochemical energy storage [136]. Composite materials contain nanocellulose to produce and save energy. To manage the temperature, paraffin at CNF core-shell composites, for example, has been designed to capture solar heat during hot seasons and release it when the temperature decreases [137]. When paraffin alone could not have produced a paper that was easily manipulated, the high-strength matrix provided by the nanocellulose was advantageous. Nanocellulose is most frequently employed in energy applications as a (super)-capacitor due to its high constant electric dipole moment, lightweight and durable mechanical properties, good optical transparency, limited porosity, the thermal expansion coefficient and air permeability [138]. A thorough and detailed study of the subject is provided for readers interested in cellulose-based supercapacitors [34,139,140]. When combined with conductive polymers and nanocarbon, nanocellulose is frequently used in charge storage devices, giving rise to a much greater specific capacitance than nanocarbon-based materials alone [141]. Costing less than 10% of that price, metal-free, all-organic supercapacitors manufactured of nanocellulose have half specific capacitance of commercial devices [142].

Graphene oxide sheets were inserted to cellulose after polypyrrole was polymerized from its surface to create supercapacitors [143]. The graphene and polypyrrole made excellent contact, resulting in a high capacitance and good conductivity. The short ion diffusion paths rendered the active sites highly accessible, eliminating the need for a binder, current collector or other additives in the composite paper. Once pyrrole became polymerized within the pores of composite, cellulose and graphene oxide were combined, creating a supercapacitor with improved conductivity and volumetric capacitance. The sole distinction between these two approaches is the order in which the polymer was applied. They seem to generate the similar morphologies and traits. Better results were obtained using a composite that had graphene sheets introduced into it after aniline polymerized around cellulose fibers from bacteria [144]. Both an energy density of 0.17 mW h/cm^2 and an aerial capacitance of 6.15 F/cm^2 were attained. The cellulose component plays a crucial role in maintaining a conductive graphene network, as seen by these values, which shown better cycle performance and are minimum three times higher than those of conventional carbon/polyaniline composites. There have been reports of a comparable substance that uses CNF rather than BNC [145]. Aniline from the surface of the nanocellulose was polymerized to provide a great surface coverage and an increase in the surface area of polymer. The material demonstrated an impressive balance between power and energy density. Aniline from the surface of the nanocellulose was polymerized to provide a great surface coverage and an increase in the surface area of the polymer. The material exhibited an impressive balance between power and energy density. A prominent advantage of using nanocellulose to enhance the mechanical properties of composite is the reduced aggregation of graphene, which improves electrical performance due to the favourable interactions between cellulose and graphene-related materials. Moreover, the incorporation of polyaniline (PANi) further enhanced the thermal stability and conductivity of the reduced graphene oxide (rGO)/nanocellulose composite. The microscopic study of the ternary composites shows that PANi nanoparticles expanded over the rGO/NC template into a spherical form, enhancing the thermal stability of composite [146].

A $LiCoO_2$/NCF/multiwall carbon nanotube paper was created and compared to other freestanding electrodes that have been described thus far, it produced a higher energy density. As a flexible battery, this composite is appealing [147]. $LiCoO_2$, carbon nanotubes and NCF were mixed in a solution to develop the lightweight, low-volume composite, which was then cast with a membrane. This paper material has an electrical capacity of 216 mAh/g at 4.7 V and an energy density by volume of 720 mAh/cm^3.

An exciting potential of nanocellulose-based materials is their ability to harvest minute amounts of energy were previously too small to capture. Several wearable and bioelectronic nanodevices work on this principle. With a little mechanical force of 16.8 N, a new nanocellulose triboelectric nanogenerator can generate 8.1 μC/m^2 of energy has been developed [148]. The nanogenerator was constructed by sandwiching a BNC film between two copper films serving as current collectors, with friction generated when the lower copper layer was pressed against the BNC, producing a voltage upon release. As a result of their different surface energies and other physical characteristics, the crushed BNC and copper films develop oppositely charged surfaces. Release causes current to flow through an external circuit, lowering the copper film and returning the BNC to its resting equilibrium condition [149].

Adsorption, decontamination, filtration and separation: Applications for the nanocellulose components include the removal of pollutants from water [150,151] and air [152], the catalytic breakdown of harmful organic compounds [153], oil contamination adsorbents [154], repellents [155,156], waterborne pathogen sensors [157] and high-efficiency energy conversion devices [158]. Mahfoudhi & Boufi [159] reviewed the potential of nanocellulose as an adsorbent for cleaning up the environment. The excellent hydrophilicity, mechanical and shape capabilities of nanocellulose to form supports and membranes during adsorption and separation operations make it highly sought-after.

Chromatographic columns have employed systems based on nanocellulose to separate chiral enantiomers, an essential process for the pharmaceutical, therapeutic, food and environmental sciences. Chiral enantiomers have traditionally been distinguished using chromatographic techniques such capillary liquid chromatography, supercritical fluid chromatography and HPLC, among others. These approaches are not the best, though, as they need complex chiral stationary phases and long analytical times. As a result, open tubular capillary electrochromatography, in particular, has become a good alternative for one-pair enantiomer separation in chiral stationary phase capillary electrochromatography. Nanocellulose is an excellent example of a chiral stationary phase. At a threshold concentration, it may transition from a hydrophilic to a hydrophobic phase [160]. Tubular column capillaries composed of nanocellulose crystals modified with 3,5-dimethylphenyl isocyanate have been employed for enantioseparation. These capillaries demonstrated broad applicability across various enantiomeric pairs, exhibiting excellent stability, durability, and reproducibility over multiple cycles [161]. Owing to their remarkable mechanical strength, large surface area, high water permeability and adaptable surface chemistry, nanocellulose-based materials are also widely utilized in water purification systems. In a new study, Tato *et al.* [162] reported the effectiveness of thin-film composites made of nanocellulose metalized with Ag and Pt nanoparticle composites over forward osmosis water treatment. For wastewater samples, this composite displayed increased water fluxes and solute rejections.

The purpose of the nanocellulose membranes was to absorb Ag^+ and other metal ions. The natural nanocellulose did not allow quick water permeability over the membrane due to its thick fibers and small pores. By functionalizing TEMPO, the surface roughness of membrane was improved, lengthening the filtering time [163]. The carboxylate groups in the TEMPO-functionalized nanocellulose system initially coordinate and organize the metal ions; upon drying, the copper ions subsequently aggregate into clusters or nanoparticles. Moreover, 1,2,3,4-butanetetracarboxylic acid has been functionalized onto nanocellulose to improve pollutant adsorption [164]. The dense nature of carboxylic acids and the ability to use several carboxylic acids to combine heavy metals greatly enhanced the adsorption capabilities for Pb(II). In a study by Liu *et al.* [165], metal ions were removed from an aqueous model of industrial wastewater using phosphorylated nanocellulose adsorbents using enzymatic means. Phosphorylation was found to significantly improve the sorption behaviour and practicality of nanocellulose. Phosphorylated nanocellulose could remove over 99% of Cu^{2+} and Fe^{3+}. It is possible to establish selectivity for a particular analyte by carefully examining the surface chemistry. Moreover, Fe(III) crosslinked CNFs were superior to other surface functions in adsorbing As(V), however dopamine modified CNF surfaces gave them a high sensitivity for Cr(VI) [166].

Copper was extracted from an aqueous solution by Mautner *et al.* [167] using phosphorylated nanocellulose sheets. As the phosphorylating agent, H_3PO_4 was used. The functional molecules on the surface of the nanopaper absorb more copper ions than the phosphate groups within. Cu(II) ions are shown by a blue area on the nanopaper's surface, demonstrating the capacity of phosphorylated nanopapers to eliminate copper. The adsorbed copper may be released from the nanopapers by easy regeneration through washing with 0.1 M H_3PO_4. Aerogels and nanocellulose membranes have been utilized to clean air. It was found that MFC films functioned admirably as CO_2 barriers, enabling the effective separation of CO_2 from CH_4 and N_2, even at significant relative humidity levels [168]. After TEMPO-oxidized cellulose nanofibrils were dispersed in *tert*-butyl alcohol and frozen, an aerogel was produced. This aerogel has a convoluted, linked macroporosity and a large surface area (300 m^2/g). These aerogels demonstrated negligible pressure decreases and were effective air filters. These simple cellulose nanofiber-based technologies outperformed traditional filters, making them compatible for application in air filtration [152]. One possible application for nanocellulose is as a covering for surfaces that can clean themselves. To this end, a straightforward physical sedimentation process has been used to cover solid surfaces with a CFR monolayer [156]. Strong surface barriers prevent hydrophobic substances from adhering and when adhesion does occur, the well-hydrated polar groups on the surface effectively dislodge them. As a result, oils of various types from polar *n*-butanol to viscous motor oil can be completely removed from the surface [156].

The unique molecular structure of CNF, along with its self-cleaning property, results in a uniform, packed and symmetrical arrangement of numerous surfaces polar hydroxyl and carboxyl groups, forming a polar corona around a crystalline nanocellulose strand.

Silver nanoparticles (AgNPs)–BC nanocomposites are currently widely used to eliminate bacterial contamination. Specifically, their potent biocompatibility and capacity to retain water have rendered them advantageous in the development of antimicrobial food packaging materials [169,170], paper with antibacterial properties for treating water [171] and nanocomposites for laundry [172,173]. Moreover, materials for wound dressings with increased antibacterial activity have been made using them. In the water treatment sector, they serve as effective substrates for substrate-enhanced Raman scattering (SERS) [174,175].

Catalysis: Over time, there has been an increase in interest in ecological friendly catalytic processes. In order to help in chemical synthesis, sterilization and the esterification of fatty acids with long chains in the formation of biofuels, nanoparticles made of metals and metal oxides have been employed as catalysts [176,177]. Catalytic applications of Ag, Au, Cu, Cu–Pd, Pd, Pt, Ru and CuO–nanocellulose hybrid composites has been investigated [172,178,179]. In order to functionalize CNC in a reducing environment for Heck coupling and catalytic hydrogenation reactions, Pd nanoparticles were used [180]. Comparisons of cellulose nanocrystals (CNC) with Al_2O_3 and carbon supports showed that, despite using less Pd and achieving 90% conversion, CNC exhibited catalytic activity that was comparable to or higher than that of the other supports. The catalytic processes appeared to be actively facilitated by the surface of CNC. Cellulose sponges prepared by double linkage cellulose with γ-glycidoxypropyltrimethoxysilane and polydopamine served as supports for Pd nanoparticles. This recyclable material was an efficient catalyst for the heterogeneous Heck and Suzuki cross-coupling reactions. Palladium leaching was very little and the catalyst was readily obtained from the resulting mixture and reused [181]. By leveraging abundant natural resources as a foundation, this approach enables more efficient use of noble metals. These novel materials surpass conventional polymer-supported metallic nanoparticles in turnover frequency, owing to their enhanced efficiency, which arises from improved nanoparticle dispersity and better coverage of the support surface. It has been shown that in ketone hydrogenation procedures, Pd functionalized CNCs may offer enantioselectivity (up to 65% enantiomeric excess). It is thought that many hydrogen bonds formed between the CNC surface and substrate are what are causing this phenomenon [182].

Through the Hinsen click reaction, it has been demonstrated that TEMPO-oxidized CNF is the perfect support for copper ions to create catalytic material [183]. Comparably, the nanoparticles of magnetite, gold and silver have been combined to the nanocellulose substance supports to form composite structures that show exceptional catalytic activity.

Thermo-stability and non-combustible: Phosphorylated cellulose provides a special blend of great heat stability and low flammability. The fact that natural cellulose and the majority of its derivatives burn cleanly and have little thermal stability is one of its key features. Inflammable substances based on halogens, nitrogen, phosphorus, metal ions and nanofillers have all been used; the most effective of these have been those based on halogens [184]. However, the use of halogen-based flame retardants raises significant environmental and health concerns. These compounds can leach from polymer matrices into the surrounding environment, accumulate in living organisms and upon combustion, generate toxic fumes. Compounds containing phosphorus promote the production of char rather than volatile, flammable species. When incendiary flame retardants come into contact with a carbon source, they react to generate a char layer, such as phosphorous acids and their salts. This layer of char insulates the material and retards the spread of fire [185]. Because of its high carbon content, cellulose may be utilized as a source of carbon in intumescent flame retardants [186]. External flame retardants, such as ammonium sulfate and diammonium hydrogen phosphate, are frequently used. When a flame retardant, such phosphate groups, is covalently attached to cellulose, it has certain advantages over applying flame retardants externally. As char formed while burning, covalently linked groups show less chemical leaching over time. This char prevents further breakdown of the surrounding polymer by acting as a thermal insulator. Chemically modified cellulose with charged phosphoric acid moieties can enhance the properties of nanocellulosic materials by functioning as a char-forming agent. Cellulose fibrils are often utilized to make safer commercial products by improving flame resistance [187,188].

Thermal characteristics of phosphonated nanocellulose were examined by Sirvio *et al.* [189]. In this work, periodate oxidation and reductive amination were utilized to add phosphonate functional groups to nanocellulose using bisphosphonate compounds. Bisphosphonate nanofibrils or nanocrystals were formed, depending on the degree of oxidation. Even at modest replacement amounts of 0.22-0.32 mmol g^{-1}, bisphosphonate nanocellulose demonstrated significant heat stability and char generating capabilities as compared to manually manufactured NFC. Thus, bisphosphonate nanocellulose exhibits potential use as both a composite reinforcement and a char-forming agent. Recently, Ghanadpour *et al.* [190] investigated renewable, naturally-occurring nanomaterials with intrinsic flame-retardant properties specifically, phosphorylated cellulose nanofibrils. Pulp fibers containing cellulose were phosphorylated using $(NH_4)_2HPO_4$ and urea. Subsequently, the material obtained underwent high pressure homogenization to yield phosphorylated CNFs. For the initial time, phosphorylated fibres were employed to make cellulose nanofibrils without requiring any additional preparation, resulting in fibrils with a width of around 3 nm and lengths ranging from 500 to 1000 nm. When phosphorylated CNFs were used to prepare nanopaper sheets, their thermal stability and flame-retardant qualities were significantly better than those of filter paper and unmodified pulp fibers. The nanopaper sheets demonstrated self-extinguishing activity and stayed ignite-free for 35 kW/m^2 in flammability tests. The fibrous forms of this material might be used to make durable, eco-friendly flame-resistant nanocoatings and composites.

Remarkably, flame resistance is also exhibited by the graphene-nanocellulose composite, as seen by 25% reduced

peak heat release rate of the composite compared to CNFs alone [191]. Compared to polymeric foams containing halogenated fire retardants, this composite material demonstrated greater resistance to burning. While phosphorylation is now the most effective method of surface modification to improve heat stability, there are several additional functional groups that serve the same purpose. By avoiding depolymerization, esterification using esters devoid of α-hydrogens, such as benzoyl and pivaloyl esters, increases the thermal stability of nanocellulose from 230 ºC to over 300 ºC [192]. By functionalizing with long chain, thermally stable amides, the beginning temperature of thermal breakdown was raised by 90 ºC [193].

Conclusion

The research findings reveal significant insights into the potential of nanocellulose materials, particularly in the realms of mechanical reinforcement, catalysis and flame retardancy. Initially, the mechanical characteristics of nanocellulose-reinforced nanocomposites were examined. The study showed that as the nanocellulose content increased up to 5 wt.%, the tensile modulus and strength of the nanocomposites improved noticeably. However, at lower nanocellulose content, adverse effects were observed, likely due to differences in failure strain between the nanocellulose and the matrix polymer. This knowledge is essential for maximizing the mechanical characteristics of nanocomposites and guaranteeing efficient stress transmission. In terms of catalytic applications, nanocellulose-based materials were found to effectively catalyze diverse cross-coupling reactions and hydrogenation processes. The use of Pd functionalized CNCs, for example, showcased promising enantioselectivity in ketone hydrogenation, indicating potential applications in asymmetric catalysis. Moreover, nanocellulose supports were utilized for the development of composite structures exhibiting remarkable catalytic activity with various nanoparticles, such as gold, silver and magnetite. Furthermore, the study highlights the unique attributes of nanocellulose materials as flame retardants. Phosphorylated cellulose, for instance, was observed for its combination of low flammability and strong heat stability, offering potential as a safer alternative to traditional halogen-based flame retardants. The research also demonstrated the use of nanocellulose in the formation of self-cleaning surfaces and antibacterial nanocomposites for applications in food packaging, water remediation, wound dressing and substrate-enhanced Raman scattering. In summary, the review presents nanocellulose as a multifaceted material with promising implications for mechanical reinforcement, catalysis and flame retardancy, thus paving the way for innovative and sustainable material development and reveals the actual data from scientiometric study.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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