detritus | Multidisciplinary Journal for Circular Economy and Sustainable Management of Residues

APPLICATION OF NANOCELLULOSE IN FOOD PACKAGING - A SWOT ANALYSIS

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Article Info:
Received:
15 September 2023
Revised:
15 March 2024
Accepted:
3 April 2024
Available online:
26 April 2024

Keywords:
Nanocellulose
Food packaging
Biodegradable plastics
Waste reduction
Waste management

ABSTRACT

Environmental concerns due to the wide use of plastic in food packaging have become one of the most significant challenges in the world. Consequently, the research in developing sustainable materials for food packaging has accelerated. Nanocellulose-based packaging is a biodegradable, renewable, and antimicrobial material with some competitive physicochemical characteristics when compared to plastic packaging. However, there has been insufficient research on a holistic discussion of the potentials and drawbacks of nanocellulose as well as its production, applications and disposal regarding sustainability. This study aims to evaluate the application of nanocellulose in food packaging in the view of environmental sustainability. It gives an exhaustive overview of the essential aspects from the production to disposal of nanocellulose through a literature review. Then, a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis is used to evaluate the potentials and drawbacks of applying nanocellulose in food packaging. It has been observed that the physicochemical properties of nanocellulose materials have the potential to be used in food packaging with fewer negative impacts on the environment. Furthermore, it supports the top tiers of the waste hierarchy and a circular economy. However, some challenges need to be addressed to ensure the safe and effective use of nanocellulose in food packaging, including high expenses, a lack of guidelines, and potential hazards to people and the environment. To eliminate these uncertainties, more studies need to be performed on applying nanocellulose in food packaging.

1. INTRODUCTION

Packaging is essential for preventing food items from spoilage, damage, contamination, or deterioration and shielding sensitive bioactive compounds from damaging physical and environmental forces (Ahankari et al., 2021; Ashfaq et al., 2022). With 85%, food packaging comprises the largest part of the whole packaging industry (Silva et al., 2020). Therefore, it is the key lever when aiming to make changes in the packaging industry. The most popular packaging materials are plastics (ibid.). Their characteristics show significant advantages in comparison to other materials and thus make them especially suitable for application in food packaging. Plastics are easy to use due to their light weight and flexibility, have low production costs making them accessible for a wide range of producers and users, and show excellent mechanical and barrier qualities which support the main goal of packaging - protecting the food items (Sangroniz et al., 2019).

In addition, Silva et al. (2020) state that the market for plastic packaging has been expanding by 20 to 25 per cent annually. In Europe, 23 million tonnes of plastic packaging are generated annually which is estimated to reach 92 million tonnes by 2050 (Ncube et al., 2021). Furthermore, since 1950, the amount of plastic waste in the world has been estimated at 6300 million tons, of which 4977 million tons have been accumulated in landfills or waterways (Silva et al., 2020). There is a growing concern about the widespread usage of petroleum-based plastics which are non-renewable, non-biodegradable, and contribute to an environmental crisis (Azeredo et al., 2017). Plastic waste that starts to decompose results in microplastic particles that intrude the food chain, carrying pollutants and hence impacting animal and human health (Azeredo et al., 2017; Chai et al., 2023). Furthermore, microplastic and global warming supplement each other and, as a result, contribute to worsening climate change (Bergmann et al., 2022).

Consequently, the need for packaging materials that are renewable (not petroleum-based), biodegradable, and cause minimal environmental impacts has increased as stated by Ahankari et al. (2021). One such substance is nanocellulose which has demonstrated exceptional promise

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Detritus / Volume 27 - 2024 / pages 3-11
https://doi.org/10.31025/2611-4135/2024.18380

for food packaging due to its availability, renewability, degradability, and physical-chemical characteristics (Silva et al., 2020). ISO/TS 20477:2017 defines nanocellulose as a structure with at least one dimension equal to or less than 100 nm, which can be subdivided into cellulose nanocrystals and cellulose nanofibrils formed chemically and mechanically, respectively (Fotie et al., 2020).

Nanocellulose is made from natural cellulose that has been fermented by plants, seaweeds, and microorganisms via chemical (Zhou et al., 2021), biological and mechanical processes like pressure refiner and grinder treatment (Sarwar et al., 2018). The reduction of the particle size improves the properties of commercial cellulose fibres (Siddiqui et al., 2023). Depending on the sources and techniques used for extraction, the types of nanocellulose have a variety of structures and sizes (Amara et al., 2021). Nanocellulose products, such as cellulose nanocrystals, nanofibrillated cellulose, and bacterial nanocellulose, have outstanding physicochemical properties that have the potential to significantly alter a variety of commercial applications like the packaging industry (Ferrer et al., 2017). Therefore, different methods of applying nanocellulose for packaging, like coating and casting have been developed (Ferrer et al., 2017).

Although most of the studies considering the application of nanocellulose in food packaging (e.g., Ma et al., 2022; Mu et al., 2019) include both positive aspects and challenges, a holistic overview and a linkage of the material's features to its production, uses and disposal are still missing in this research field. Therefore, due to the importance of a thorough discussion, this study aims to systematically evaluate to what extent the application of nanocellulose in food packaging can potentially alter and minimise food packaging waste. To achieve this, two objectives are addressed, including (1) to examine the production processes, current uses of nanocellulose in food packaging and its disposal, and (2) to identify and discuss potentials and drawbacks of nanocellulose in food packaging in the view of sustainability and circular economy.

2. METHODS

The methodology of the study consisted of two parts. The first objective was met by a literature review. Moreover, a SWOT analysis was conducted to meet the second objective mentioned above. The main area of study was limited to a circularity and sustainability perspective, especially environmental sustainability, which creates the system boundaries of the analysis. Therefore, technical aspects are included to an extent where they support answering the objectives but not described in detail. The period of the literature considered is 10 years, therefore only studies completed and published after 2013 are analysed. This was brought on by how quickly the field of technology research was developing. Furthermore, a study conducted by Garrido-Romero et al. (2022) has shown a rapid abundance of publications focusing on nanocellulose in food packaging within the past ten years, supporting the chosen timeframe. Since the study was technology-focused, there was no geographical restriction. In addition, as the title implies, nanocellulose's application in food packaging was the study's sole emphasis.

The first objective comprises a literature review of the production processes, applications and disposal of nanocellulose. To gather information on those areas, the following keywords were applied: “nanocellulose” OR “cellulose” OR “cellulose nanofibres” OR “cellulose nanocrystal” AND “production” OR “sources” OR “processes” OR “applications” AND “food packaging” OR “disposal”. To find full-text articles that meet the aforementioned requirements, the databases Scopus, ScienceDirect, Google Scholar and Wiley Online Library were used.

The second objective was additionally accomplished by conducting a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis using the information extracted from the literature. This well-established approach was chosen because it facilitates decision-making through evaluating and comparing potentials and downsides as emphasised by Puyt et al. (2023) and Yuan (2013). Previous SWOT assessments in the context of environmental and waste management have evidently demonstrated potentials of improving the systems in question (Yuan, 2013).

In order to choose matching keywords that would facilitate finding appropriate literature for the SWOT analysis, the previously mentioned study conducted by Garrido-Romero et al. (2022) was consulted. The most common keywords in the context of nanocellulose in food packaging were analysed. Based on these results, the following keywords were applied in the literature review: “nanocellulose” OR “cellulose” OR “cellulose nanofibres” OR “cellulose nanocrystal” AND “food packaging” OR “waste” OR “plastic waste”. The databases used for research were the same as mentioned in the first objective.

3. RESULTS

3.1 From production to disposal of nanocellulose

3.1.1 Production processes

Salimi et al. (2019) state that the main steps in producing nanocellulose are (1) selecting proper cellulose sources, (2) pre-treatment, and (3) extraction. Firstly, choosing appropriate cellulose sources, like those with a high cellulose content, is one of the most significant factors in the production of nanocellulose (Salimi et al., 2019). With regard to this, Ferrer et al. (2017) emphasise that the source of cellulose influences the characteristics of the produced nanocellulose, such as morphology, size and crystallinity. For instance, when materials like wood, sugar beets, or potato tubers are used as the source, the diameter of the nanocellulose produced ranges from 5 to 60 nm (Klemm et al., 2011). Wood has a porous structure that combines high strength and low density (Kargarzadeh et al.,2017). On the other hand, when low-molecular-weight sugars and alcohols are used for nanocellulose production, the diameter of the resulting nanocellulose ranges from 20 to 100 nm (Klemm et al., 2011). Cellulose nanocrystals, which are a type of nanocellulose, are mainly sourced from materials like wood, cotton, tunicin, algae, and bacteria with a diameter ranging from 5 to 70 nanometers (ibid.). Cellulose nanocrystals have excellent mechanical properties (Kargarzadeh et al., 2017).

Secondly, according to Palacios Hinestroza et al. (2019), pre-treatment is required to eliminate impurities and lower energy consumption during the mechanical breakdown of cellulose. Each type of biomass source consists primarily of cellulose, lignin, hemicellulose, pectin, and other smaller components that have various physical and chemical properties which hence require different pre-treatment methods (Lunardi et al., 2021). These can be broadly divided into two groups, non-biological and biological, depending on the type of treatment process applied. Physical, chemical, and physico-chemical pre-treatment methods are the three main categories of non-biological pre-treatment techniques, which do not use any microbiological treatments. Kumar and Sharma (2017) have reviewed the characteristics and applicability of the most common methods. According to Ko et al. (2020), alkaline pre-treatment, which is an eco-friendly method, can increase the production of nanocellulose by removing 73% of hemicellulose and 50% of lignin from wood fibre. So, pre-treatment makes the cellulose accessible for the procedure.

Thirdly, there are three main extraction processes for producing nanocellulose: mechanical, chemical, and biological (Salimi et al., 2019). The different processes lead to variations in the types and characteristics of the produced nanocellulose (Phanthong et al., 2018). Mechanical processes utilise mechanical forces that cause the cellulose to become defibrillated and create a crucial tension centre in the fibrous substance (Salimi et al., 2019). According to Phanthong et al. (2018), the most common mechanical techniques are ultrasonication (using ultrasound for defibrillation) and high-pressure homogenization (by injecting cellulose slurry into a container at high pressure and speed). Chemical processes employ chemical substances (such as acid hydrolysis and metal salts) that break down the cellulose. The most common chemical process is acid hydrolysis, which uses sulfuric acid to isolate nanocellulose from cellulosic materials and break down the disordered regions (Phanthong et al., 2018). Moreover, different factors, including reaction temperature, time, acid type, and acid concentration, have a substantial influence on the process (Tiwari and Sanjog, 2023). Biological processes are applied when cellulose is degraded by biological reactions (Salimi et al., 2019). Enzymatic hydrolysis is one example of a biological process that uses enzymes to break down or change cellulose fibres (Phanthong et al., 2018). This process often requires moderate conditions. Since this process takes a lot of time, it is always combined with another technique (ibid.).

To optimise the production process, researchers have also combined several of these extraction strategies (Ferrer et al., 2017). The introduced processes highlight the variety of methods available for producing nanocellulose. This helps understand how the environmental impacts of nanocellulose can be minimised starting from the early stages of the material's lifecycle.

3.1.2 Uses in food packaging

Thermoplastics are a major conventional plastic category commonly used in food packaging since they become soft when heat is applied (Marsh and Bugusu, 2007). Thermoplastics most widely used in food packaging are polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene (ET), and polyethylene terephthalate (PET). The properties of the different thermoplastics are mainly influenced by the composition of the raw materials and physical and environmental conditions (such as linearity and molecular weight) (Teck Kim, Min and Won Kim, 2014). They have shown good performance in terms of thermal and mechanical behavior, water vapor transfer rate, gas permeability, and chemical resistance (bid.). They are also lightweight and low-cost, which makes them suitable for food packaging applications (Ncube et al., 2021). However, they are nonbiodegradable, derived from fossil fuels, and responsible for different environmental issues like the emission of greenhouse gases (ibid.), underlining the need of more environmentally friendly alternatives, such as nanocellulose.

Nanocellulose has a variety of uses in the food packaging industry. According to Ma et al. (2022), the most common application of nanocellulose is as a reinforcing phase for food packaging materials, although it may also perform as matrices for other materials. Moreover, Mu et al. (2019) emphasise that nanocellulose is added to traditional polymers to improve mechanical and biodegradable characteristics. Nanocellulose can be incorporated in two different ways. It can be coated to traditional food packaging, in the form of films, for instance, or by fabricating multi-layer materials, through casting and evaporation, extrusion, and layer-by-layer (Ashfaq et al., 2022; Ferrer et al., 2017).

It is well-recognized that coatings are an efficient and sustainable technique for integrating nanocellulose into food packaging (Fotie et al., 2020; Li et al., 2015). The coating improves several qualities of food packaging materials (Li et al., 2015), including antibacterial capabilities, moisture retention, control of food oxidation, and providing the substrate with different types of barriers (like water, oxygen, and grease) (Fotie et al., 2020). Furthermore, there is the possibility of using edible and environmentally friendly polymers that are either dipped or coated directly onto the food surface (Li et al., 2022; Zhang et al., 2021).

According to Li et al. (2022), casting is one of the simplest methods for producing nanocellulose packaging materials. It is a process that involves drying films of neat or modified nanocellulose by evaporating water or solvent from the nanocellulose at a specific temperature (Ferrer et al., 2017). It enhances mechanical and water resistance characteristics, increases tensile strength, decreases water solubility, and leads to high UV resistance (Ferrer et al., 2017; Li et al., 2022). Extrusion is an economical and productive method to fabricate nanocellulose films, creating good oxygen and water vapour barrier qualities (Li et al., 2022). In addition, the material is extruded via an extruder fitted with a metal die in the appropriate pattern to make the required shape (ibid.).

In the layer-by-layer method, a skinny layer of functional substances deposits onto surfaces. Fotie et al. (2020) emphasise that it takes numerous coats of nanocrystal cellulose dispersions on solid layers to achieve the necessary thickness to meet the demands for wet strength, mechanical qualities, and gas barrier capabilities. In conclusion, the variety of nanocellulose applications provides a widespread base for working with nanocellulose in food packaging. In particular, coating and casting options hold positive aspects that will be elaborated on in the SWOT analysis.

3.1.3 Disposal

The end-of-life stage is disposal, a significant phase in circular economy. A vital part of circular economy is looping the waste flow into producing new goods and services (Johansen et al., 2022). Nanocellulose packaging can facilitate the transition from a linear economy to a circular economy in different ways. Firstly, recycling and composting are two main methods for the disposal of nanocellulose (Shahzad et al., 2023; Shanmugam et al., 2019), offering a promising approach to closing the resource cycle, improving the environmental situation and retaining value (Meister et al., 2022). In contrast, using conventional plastic, which most often follows a linear economy (production, use, and disposal), can pose severe threats to the environment and human health (Johansen et al., 2022). Secondly, the production of nanocellulose from wastes (such as food or agricultural waste) aligns with the principles of the circular economy (Mateo et al., 2021).

Since nanocellulose is biodegradable and non-toxic, composting is an affordable and environmentally friendly way to dispose of the material along with other organic waste, which also contributes to lowering the quantity of waste that ends up in landfills (Shahzad et al., 2023). The packaging will decompose into its natural compounds, such as water and carbon dioxide, and can then be used as a nutrient-rich soil fertiliser (Fotie et al., 2020).

Some types of nanocellulose-based materials can be fully recycled several times or converted into other valuable materials like carbon black, a material mainly used as a pigment and reinforcement in vehicle tyres (Uttaravalli et al., 2022), in the recovery process (Shahzad et al., 2023; Shanmugam et al., 2019). Shanmugam et al. (2019) recycled nanocellulose films into films with approximately 70 percent of the primary film's strength. The process of recycling leads to a lower density, less homogeneity, and poorer strength. However, the recycled nanocellulose materials were still able to deliver acceptable performance for most packaging applications. The disposal options of nanocellulose and its recycling ability have an impact on its use and will be a factor in the following SWOT analysis.

3.2 SWOT analysis of nanocellulose in food packaging

The following SWOT analysis determines potentials and drawbacks of nanocellulose in food packaging. All aspects are chosen with regard to nanocellulose's role in and contributions to sustainability, namely environmental impacts, and its potential of circularity according to the system boundaries aforementioned. This includes chemical and physical details that impact the mentioned perspectives but excludes a deep dive into technical details.

3.2.1 Strengths

Nanocellulose incorporated into packaging is biodegradable, compostable and easily recyclable, without causing any environmental harm (Arrieta et. al, 2016; Fotie et al., 2020). By-products from recycling nanocellulose can be used in a different context, as mentioned before (Shahzad et al., 2023). It can be obtained from a wide range of biological sources (Silva et al., 2020). Depending on the source, nanocellulose is relatively low in price, compared to other biodegradable plastics alternatives (Arrieta et al., 2016; Siddiqui et al., 2023). According to Fotie et al. (2020) and Silva et al. (2020), nanocellulose is biocompatible and non-toxic. Regarding chemical properties, the material has high crystallinity and high polymerisation (Perera et al., 2022; Silva et al., 2020). Resulting of the decreased particle size, cellulose nanofibres show improved properties with regard to an increased surface-to-volume ratio and improved mechanical properties, such as thermal stability or tensile strength (Siddiqui et al., 2023; Silva et al., 2020). Furthermore, this leads to light weight and low density (ibid.). Using nanocellulose as a coating for food packaging made of paper, the material's gas barrier qualities are improved (Fotie et al., 2020; Garrido-Romero et al., 2022).

Nanocellulose can make the nanomaterial-based films more tortuous, which causes diffusion processes to move more slowly and lowers permeability (Yu et al., 2014). Moreover, nanocellulose and other bio-nanocomposites usually show strong antimicrobial, oxygen-scavenging, and ethylene-absorption activities (Perera et al., 2022). Oxygen-scavenging refers to the process of reducing oxidative damage in a wide range of food constituents, such as oils and fats, to prevent rancidity, discolouration, and loss of taste and nutritional components (Vermeiren et al., 2003). Absorbing ethylene in food items helps extend their shelf life (Ayhan, 2019). Moreover, nanocellulose has a strong ability to inhibit lipid oxidation and high moisture control (Machado et al., 2022; Siddiqui et al., 2023). These characteristics are essential for reducing microbial growth, and improving the quality and safety of food products during storage and transport (ibid.) which assists in extending the food items' shelf-life (Ashfaq et al., 2022) and, consequently, reduces the amount of food going to waste. Besides, these properties reduce the need for fossil fuels when using nanocellulose (Souza et al., 2020).

3.2.2 Weaknesses

When compared to plastics, nanocellulose has some drawbacks. It is not as affordable and accessible (Perera et al., 2022). Compared to conventional coating plastics, the production costs of nanocellulose are higher since it requires more machinery (Fotie et al., 2020). While plastics can be utilised in all food packaging applications, the present bio-nanocomposites are particular to the type of food (Perera et al., 2022). Since nanocellulose is most often obtained from plants in which water is an integral part, the material itself has weak water resistance, making it inappropriate for environments with high humidity (Ahankari et al., 2021; Solhi et al., 2023). It further lacks the ability to be sealed by heat, which is the most frequently used method to form and close plastic packaging (Fotie et al., 2020; Ilhan et al., 2021). Because biodegradable packaging is novel, research must be conducted to develop it into a global standard for food packaging (Perera et al., 2022). Also, there are not sufficient regulations and legislation regarding the use of bio-nanocomposites in food packaging (ibid.).

3.2.3 Opportunities

Nanocellulose can be obtained from a variety of wastes, including barley waste, tomato peels, garlic straw residues, wood waste and paper waste, corncob residue, exoskeleton of prawns and crabs, and industrial waste cotton (Noor et al., 2020; Silva et al., 2020). Consequently, by being produced of waste, the nanocomposite supports a circular economy and is recognized as more sustainable than conventional plastics (Siddiqui et al., 2023). This makes nanocellulose a great alternative for large-scale applications, such as packaging for beef meat (Machado et al., 2022; Siddiqui et al., 2023). The characteristics of polymers, including their thermal, mechanical, barrier, and surface wettability properties, could all be improved with the addition of nanocellulose to the existing material (Arrieta et al., 2016). As a result, biobased and biodegradable polymers perform better thermomechanically (ibid.).

The combination of nanocellulose with biodegradable additives can strengthen its characteristics or mitigate some of its flaws: By combining nanocellulose with gelatin, starch, gelatin-based biopolymers, or other bioplastics, the above-mentioned lack of water resistance can be improved (Garrido-Romero et al., 2022). Adding essential oils, such as thyme, gives the material an antioxidant activity, which restricts the oxidation of proteins, lipids, DNA, and other molecules by preventing the growth stage in oxidative reaction chains (Atasoy et al., 2019; Machado et al., 2022). With further nanocellulose applications, waste disposal and greenhouse gas balances will be reduced, promoting environmental sustainability (Abdul Khalil et al., 2016). Moreover, research into the use of nanocellulose in food packaging is a hot topic in the sciences right now (Garrido-Romero et al., 2022).

3.2.4 Threats

Although using nanocellulose in food packaging has many benefits, there are some concerns as well. One is that the adoption of nanotechnology in society and the economy is still unclear because of consumer and manufacturing worries about worker safety and health due to potential environmental harm, and human health effects like cancer and gastrointestinal tract inflammation (Souza et al., 2020). Also, given the absence of guidelines and assurances for the effectiveness of its implementation, the package manufacturers have not yet demonstrated a strong interest in the applicability and processability of nanocellulose (Fotie et al., 2020). Another risk that might affect the usage of nanocellulose in food packaging is its potential migration to foods which has not yet been studied (Ashfaq et al., 2022; Azeredo et al., 2017; Souza et al., 2020). Given the novelty of bio-nanocomposites in food packaging, the migration levels and the cytotoxicity effects of nanomaterials are still poorly understood (Perera et al., 2022). Furthermore, advantages of conventional plastics pose a threat to an extended integration of nanocellulose in food packaging. Their longevity, low production price and broad possibilities of application make it difficult for many alternatives to prevail on a large scale (Fotie et al., 2020; Perera et al., 2022; Sangroniz et al., 2019). Other than conventional plastics, nanocellulose's particularity to a type of food, as mentioned in Perera et al. (2022) limits its applicability in food packaging implementations. Additionally, despite the awareness of problems with plastics, current human behaviour and habits often impede the change to other solutions (Heidbreder et al., 2019). Due to these reasons, nanocellulose encounters difficulties outcompeting conventional plastics and establishing on the markets.

Table 1 summarises this SWOT analysis of nanocellulose in food packaging. Overall, nanocellulose used in food packaging offers numerous strengths, such as being easily recyclable and extractable from a variety of biological sources. It does, however, have some weaknesses, e.g., not being as accessible and affordable as plastics, and not being covered in enough laws and regulations. Opportunities that prevail for nanocellulose include enhancing the properties of polymers and promoting a circular economy. There are also threats, though, such as the potential migration to food and the connected unclear adoption of nanocellulose by consumers and manufacturers.

4. DISCUSSION

In the results, both the life cycle of nanocellulose (from production to disposal) and the SWOT analysis showed positive and negative aspects of nanocellulose in food packaging with regard to circularity and environmental sustainability. Other perspectives such as social aspects and technical details were not in focus of this study which has to be kept in mind when critically discussing potentials of nanocellulose.

4.1 Production, application, and disposal of nanocellulose

The current production processes, applications and disposal options of nanocellulose in food packaging are already promising. According to Ferrer et al. (2017), its potential will probably increase with further research. This is due to the fact that more knowledge about nanocellulose can reduce insecurities with regard to environmental and health issues and improve production and application procedures. Further development of the processes and their combination could simplify production, and also reduce costs and resource use as underpinned by Salimi et al. (2019). Nevertheless, current processes already allow for a more individually designable implementation as producers can choose between three different approaches; mechanical, chemical and biological. Additionally, the diverse possibilities for applying nanocellulose in food packaging, such as coating and the layer-by-layer method, are connected to different characteristics and advantages and thus make its use customisable.

However, concerning the production, use and disposal of nanocellulose in food packaging, from a circularity and environmental sustainability perspective, several restricting aspects have to be taken into account. Firstly, in addition to wisely choosing the extraction process, both an appropriate cellulose source and pre-treatment play a ma-

TABLE 1: SWOT table for the application of nanocellulose in food packaging.

Strengths	Weaknesses
• Biodegradable • Compostable • Recyclable • Can be obtained from a wide range of biological sources • Relatively low price compared to other biodegradable plastic alternatives • Biocompatible • Non-toxic • High crystallinity and polymerisation • High thermal stability and tensile strength • Low weight • Low density • Lowers permeability in applications • Improves gas barrier properties in paper packaging • Antimicrobial • Oxygen-scavenging • Ethylene-absorbing • Inhibits lipid oxidation • High moisture control • Supports high-quality and safe food storage and transport, increasing the items' shelf-life • Reduced dependency on fossil fuels	• Less affordable and accessible than conventional plastics • Higher production costs than conventional plastics • Particular to a type of food • Low water resistance in itself • No thermosealability • Lack in research • No global standards and sufficient regulations/legislation
Opportunities	**Threats**
• Variety of waste can be used to obtain nanocellulose • More sustainable than conventional plastics • Supports circular economy • Applicable on a larger scale • Combination with other components improves their properties • Biodegradable additives can improve the lack of water resistance • Addition of essential oils gives the material antioxidant activity • Helps reduce waste disposal and greenhouse gas emission • Important current research topic	• Potentially harming the environment and human health causing insecurities for consumers and manufacturers • No guidelines and assurances for manufacturers • Potential migration to foods • Potential cytotoxicity • Advantages of conventional plastics: longevity, low production price, applicability • Human behaviour and habits (social resistance to change)

jor role as supported by Ferrer et al. (2017) and Salimi et al. (2019). Regarding use and disposal, for instance, when using nanocellulose as a coating, the substrate material has to show disposal properties similar to nanocellulose to ensure that the coatings' positive characteristics are not overshadowed. In addition, although recycling nanocellulose food packaging is possible, its limitation due to the downgrading of several characteristics, as explored by Shanmugam et al. (2019), should not be forgotten.

4.2 Problems with nanocellulose and potential solutions

The SWOT analysis shows several positive aspects of nanocellulose in food packaging. Nevertheless, the severity of the elaborated weaknesses and threats is partly still uncertain. For example, the potential harm to the environment and human health must be further examined as stated by Li et al. (2015). In particular, there is research and data missing on the migration of toxic compounds to food and its consequences, among others specified by Ashfaq et al. (2022), Machado et al. (2022) and Perera et al. (2022). This threat could be remediated by only using nanomaterials whose risks are studied and known, such as non-toxic and allergy-free components. However, this might limit the number of usable nanomaterials not because they are not suitable but due to the lack of data. Another weakness is nanocellulose's inability to be heat sealed which might make nanocellulose in food packaging incompatible with current packaging processes and calls for a combination with sealable materials as mentioned by Fotie et al. (2020). Moreover, the more expensive and complex production in comparison to conventional plastics as well as difficulties to change human behaviour might hinder further implementation of nanocellulose in food packaging significantly.

A solution to reduce or eliminate several drawbacks could be the involvement of authorities as supported by Siddiqui et al. (2023) and Souza et al. (2020). In particular, missing guidelines, standards, and assurances for manufacturers could be reduced by working towards new legislation and regulations. Clear guidelines support both the approach of research and the later usage of nanocellulose in food packaging. Although nanocellulose in food packaging is still in research and far from being fully implemented, starting to develop and define a standard would improve the later uniformity of this technology. Additionally, assurances would reduce risks for manufacturers and encourage them to invest in this approach. Furthermore, subsidies on research and production of nanocellulose would reduce their costs and make the technology more attractive.

4.3 Possibilities offered by nanocellulose

Realising those suggestions would strengthen the positive aspects found in the SWOT analysis which comprise a large part of the found data as can be taken from Table 1. An example is the combination of nanocellulose with other components which increases its flexibility in applications and is thus a promising research field as emphasised by both Ashfaq et al. (2022) and Ferrer et al. (2017). The outcome of this research is still open as the variety and number of possible composites are broad. Furthermore, nanocellulose outcompetes conventional plastics in terms of disposal by contributing both to a decrease in waste amounts and waste types. This is due to the reduction of plastic packaging or coating thickness, the possibility of fully replacing plastic coatings, its good compostability and recyclability and the several applications of composted or recycled nanocellulose food packaging.

Therefore, nanocellulose supports a circular economy and promotes two of the upper levels of the waste hierarchy: waste prevention and waste recycling. The highest level, waste prevention, is achieved by reducing waste amounts and types as mentioned above. Additionally, nanocellulose's capability to decrease microbial growth can extend the freshness and quality of stored food which, in return, may avoid food waste since less food has to be disposed of due to spoilage, as stated by Siddiqui et al. (2023). The third highest waste hierarchy level, waste recycling, is supported both by using a variety of waste sources to produce nanocellulose and by nanocellulose's own beneficial characteristics with regard to its recycling.

4.4 Limitations and uncertainties

As the conducted literature review used peer-reviewed academic publications, the quality and reliability of the results are assumed to be high. However, the study's focus on environmental aspects and possibilities of circularity limited the analysis and discussion, and excluded not only a technological, but also a social perspective. A more socially oriented study could, for example, focus on environmental awareness and a shift in society's mindset towards more environmentally friendly and circular packaging options. In addition, the data availability restricted a further, more detailed study which requires more research in this still-very-new area. A more systematic and broader literature review delivering more SWOT features for future research is desirable. Moreover, SWOT analysis has some limitations. It accords equal weight to all factors and does not offer any solutions or plans of action. Therefore, the SWOT analysis conducted could be supplemented by quantitative or semi-quantitative approaches that include prioritisation of the found aspects to remediate issues by evaluating their severity and significance for the implementation of nanocellulose in food packaging.

5. CONCLUSIONS

Given the fact that plastics are the most common food packaging material, yet cause various harmful environmental effects, finding biodegradable alternatives to them has become one of the main research fields in waste prevention and recycling. Nanocellulose is one that has drawn the attention of researchers. Its characteristics have been studied in the past. However, an extensive analysis of potentials and drawbacks with regards to environmental sustainability and circularity has not been conducted yet. By performing a literature review, it was evaluated how nanocellulose is produced, currently used in food packaging and disposed of. The potentials and drawbacks of nanocellulose as an alternative to conventional plastics were analysed through a SWOT analysis.

Three steps of producing nanocellulose have been identified and described, namely selecting cellulose sources, pre-treatment, and extraction. As manufacturers can select from three alternative approaches - mechanical, chemical, and biological -, current production procedures allow for an individually designable implementation. The study revealed a variety of applications which were divided into coating for conventional food packaging and multi-layer materials. The different possibilities for using nanocellulose in food packaging were linked to its characteristics and benefits, making the use customisable. The safe disposal of nanocellulose is not much hampered; in fact, it outperforms the disposal of plastics. The main potential of nanocellulose is found in its features, which are overall beneficial for use in food packaging. Also, it supports the top tiers of the waste hierarchy. The novelty of the study field, as well as high expenses, a lack of norms or guidelines, and potential hazards to people and the environment, all contribute to the weaknesses.

Given the novelty of the research field, some threats of nanocellulose are not yet fully understood, most notably the potential migration to food. Further research is required on this topic to evaluate the harm nanocellulose may have in food packaging and whether it is applicable on a larger scale. Overall, as the demand for sustainable packaging materials continues to grow, the potential of nanocellulose in food packaging on a larger scale could rise, contributing to a more sustainable future for all.

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