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Proceeding Paper

Production of Low-Cost Nano-Functionalized Bacterial Cellulose Films for Smart/Intelligent Packaging †

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Abstract: Petroleum derived polymers such as polyethylene and polypropylene are commonly used in food packing industries while knowing the fact that these polymers cause serious threat to the ecosystem. Therefore, the development of low-cost, environmental friendly and biodegradable polymer to address these issues is an urgent need of the hour. Bacterial nanocellulose (BNC) with extraordinary and differentiated properties is gaining special attention in food packaging industry. To reduce the cost several low-cost substrates are utilized for production of BNC. Therefore, the present study is focused on the production of low-cost BNC and its subsequent functionalization for smart packaging applications.

Keywords: bacterial cellulose; low-cost substrates; halochromic materials; nanomaterials; freshness indicator

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1. Introduction

The use of smart packaging system composed of biodegradable polymeric materials has gained a recent research attention due to various unique properties in comparison to the petro–chemical based plastics [1,2]. Further, the widespread use of petroleum–derived plastics in packaging and its disposal have become a major concern due to its negative impact on environment. In view of this, the design and fabrication of various biodegradable packaging materials from natural and biological origin have attracted several research attention in recent years [3,4]. The basic functions of smart packaging are to maintain food quality and safety, prolong the shelf life, and inform the consumer about the quality of food with real time monitoring techniques. The real time monitoring can be accomplished by biosensors, time temperature indicators, or gas indicators, which sense, detects, or monitor the internal or external change in the product zone [5]. The indicator is most useful in frozen foods as maintenance of food quality and safety is an important parameter during storage and transportation. The cost of the biopolymer is an important aspect that need to be assessed for successful commercialization of this process.

Among various natural polymeric materials, cellulose obtained from bacterial origin retains several extraordinary and differentiated properties which can be an ideal material for food packaging [6]. Among several bacterial species (*Achromobacter*, *Alcaligenes*, *Aerobacter*, *Agrobacterium*, *Azotobacter*, *Pseudomonas*, *Rhizobium*), *Komagataeibacter* is known to be the industrial important strain for the production of cellulose while utilizing several carbon/nitrogen source [7,8]. However, the cost of substrate that accounts 60–70% of the total production cost and low is one of the major hindrances in successful commercialization of the process [9]. In addition to production cost, low BC yield and weak mechanical properties are the other parameters that hinders its further application in many sectors.

In view of the above limitations, the present review focused on the production of low-cost bacterial nano-cellulose for smart packaging applications. The use of various low-cost substrates for the production of bacterial cellulose, microorganisms used, and process conditions are discussed in details. In addition, the incorporation of nanomaterials and colorimetric indicators in the cellulose matrix for smart/intelligent packaging applications are highlighted.

2. Low-Cost Substrates for Production of Bacterial Cellulose

The conventional medium used for the production of bacterial cellulose is expensive and contains defined chemicals like glucose, yeast extract, peptone, ethanol, etc. [10]. The most common medium used for the production of bacterial cellulose is HS (Hestrin and Schramm) medium which is composed of glucose, yeast extract, peptone, citric acid, disodium phosphate [11]. The use of pure chemicals in defined medium increases the production cost of the process while limiting its large-scale production and industrial applicability. Therefore, finding a new effective and low-cost media that can promote high yield and reduce the production cost is essential. In view of this, several low-cost medium/waste substrates are explored for the production of bacterial cellulose which include agricultural waste, crude glycerol, wastewater, food waste, fermentation wastewater, fruit juices, etc. A summary of available literatures on production of bacterial cellulose from different wastes/low-cost substrates are given in Table 1. The utilization of these waste substrates also reduce the environmental hazards associated with these upon disposal to the environment. BC is synthesized extracellularly by both wild and mutant bacteria such as *Acetobacter*, *Gluconacetobacter*, *Azobacter*, *Pseudomonas*, etc. While, *Gluconacetobacter hansenii*, *Gluconacetobacter xylinum*, and *Gluconacetobacter pasteurianus* are most effective and widely used strains for the production of BC while utilizing diverse substrates.

Table 1. Various low-cost/waste substrates used for the production of bacterial cellulose.

Waste Source	Source
Agricultural wastes	Corn straw, wheat straw, sugarcane straw, sweet sorghum, tobacco extract, cashew tree residues, pecan nutshell, oat hulls, silver grass, elephant grass
Industrial wastes	Waste water of candied jujube, rice noodle processing, industrial hardwood, citrus pulp water, coconut water, sugar beet molasses, cheese whey, bovine whey powder, sweet lime pulp, rice wine distillery, waste beer yeast, crude glycerol residue, cellulose based textile, cotton based waste textiles, coffee cherry husk
Food waste	Starch kitchen wastes, pear peel and pomace, grape skins, citrus peel and pomace, potato peel, orange peel, cashew apple juice, orange juice, lemon peel, grapefruit juice, maple syrup, carrot juice, pineapple peels, mango peels, *Mangifera indica* extracts, rotten banana, vegetable oil, tapioca waste

3. Incorporation of Nanomaterials

The incorporation of nanomaterials into the BC matrix has improved its properties for several applications. These modification of BC can further improve or add additional features to the matrix such as antimicrobial activity, catalytic activity, electromagnetic property, antioxidant activity, etc. and can be done by modifying the surface of BC. A detailed discussion on various types of surface modification has been given in recent review by Aziz et al. [12]. In this process, the BC matrix acts as the scaffold to support the reinforcement materials, while the reinforcement materials improves the biological and physico-chemical properties of the composite matrix. A wide range of reinforcement materials including natural and synthetic polymers, nanoparticles, inorganic nanomaterials are explored for the synthesis of BC composites. Among nanoparticles, metal nanoparticles (Fe, Ag, Au, Ni, Pd, Pt), metal oxide nanoparticles (MgO, CuO, FeO, ZnO, etc.), and carbonaceous materials (carbon nanotubes, graphene) are successfully used during this process. Incorporation of these nanoparticles improve the mechanical, rheological, moisture uptake properties, antimicrobial properties of the BC composite. Silver, nano-zinc oxide, nano-titanium oxide NPs are used in recent past for the development of anti-bacterial nano-packaging products. However, the major drawback of this process is the migration of these nanoparticles from the packaging materials to the food sample and causing carcinogenicity [13,14].

4. Intelligent Packaging

In addition to the development of bio-based polymers for packaging, the modern-day packaging materials also inform the real-time quality of food to the consumer and its suitability for consumption. These intelligent/smart packaging system monitor the freshness, microbial growth, and any other chemical changes of the product by measuring the change in pH, temperature, humidity, production of gases such as ammonia, ethylene, carbon dioxide, hydrogen sulfide and volatile compounds, and pathogens and their metabolites [15,16]. The use of synthetic indicator in food packaging applications are less preferred due its toxicity, carcinogenic property, and its ability interfere in biological systems. Hence, colorimetric indicators from natural sources are promoted. Among different sensors used in smart packaging applications, natural indicators are most preferred due to its biodegradability, easy preparation methods, less toxicity, eco-friendly nature, low cost, etc. [17]. These natural halochromic materials are incorporated into the cellulose nanocomposite matrix and change their color with the change in physiological condition of the packaged food. A list of natural colorants and its sources are given in Table 2. A schematic representation of the process is shown in Figure 1.

Table 2. Summary of natural colorant and its sources. Adopted and revised from Alizadeh-Sani et al. [17].

Natural Colorant	Sources
Anthocyanins	Apple, elderberry, blackberry, nectarine, plum, peach, red cabbage, grape, beans, eggplants, strawberry, red radishes, cranberries, blueberries, plums, cherries, purple corn, red berries
Carotenoids	Carrot, egg, orange, chicken fat, Yellow corn, egg, liver, yellow corn, tomato, pink grapefruit, palm oil, paprika (*Capsicum annum* L.), lobster, shrimp, salmon, berries, annatto seeds
Betalains	Beets, *beta vulgaris* L. roots, caryophyllales, fungi, flowers of the cactus *mammillaria*, *Opuntia ficus-indica* [L.] Miller fruits *Opuntia* cactus, *Hylocereus polyrhizus* (Weber) Britton & Rose fruits
Chlorophylls	Universal (nettle, spinach and grass and etc.), mostly plants, Cyanobacteria, various algae
Anthraquinone/Naphthoquinone	Aloe vera, cassia species, *Cassia alata*, *Prismatomeris sarmentosa*, *P. glabra*, *Morinda citrifolia*, *M. elliptica*, *Hedyotis capitellata*, *Rennellia elliptica*, *senna*, *rhubarb*, *Dactylopius coccus*, bacteria, marine sponges, fungi, lichens, insects
Curcumin	Curcuma longa (rhizomes), ginger family

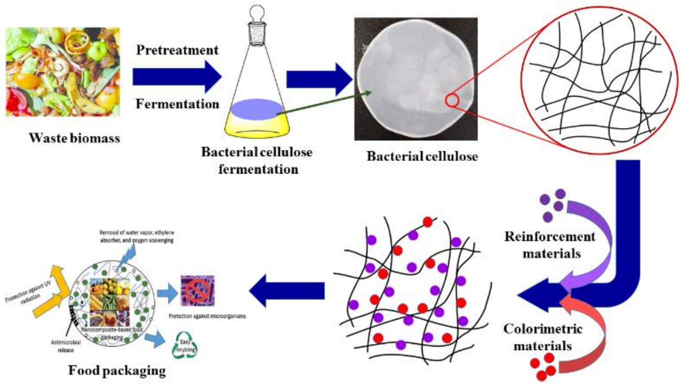

Figure 1. A schematic representation of development of cellulose nanocomposite from waste/low cost substrates and its subsequent application in intelligent packaging.

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