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Nanotechnology in Food: Processing, Packaging, and Preservation

Aqsa Jamshaid[1*], Shumaila Ibrahim[1], Adeeba Ali[1], Muhammad Basim[1], Aliyya Atta[1], Muhammad Asjad Haseeb[1], Sami Ullah[1], Muhammad Bin Saleem[1] and Manam Walait[1]

[1]Department of Biotechnology, Faculty of Science and Technology, University of Central Punjab, Lahore, Pakistan

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***Corresponding Author:**
Aqsa Jamshaid
Department of Biotechnology, Faculty of Science and Technology, University of Central Punjab, Lahore, Pakistan
aqsajamshaid4@gmail.com

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ABSTRACT

Nanotechnology entails creating, characterizing, and employing structures with sizes ranging from 1 to 100, significantly influencing medicine, engineering, agriculture, and food. Nanomaterials hold potential for the development of high-quality, healthier, and safer foods improving shelf life and reducing contaminations. Food safety and security are gaining much attention globally to maintain a consistent supply of nutrient-rich and safe food. Many disciplines of food science have been changed by the rapid growth of nanotechnology, particularly those involving food storage, processing, functioning, packaging, transportation, and other safety considerations. This review focuses on current advancements in food nano-packaging, such as active, smart, and improved packing. Nano-encapsulation improves food processing by releasing bioactive chemicals, increasing bioavailability, and extending shelf life. Additionally, applications of nanotechnology in agriculture and food, including nano-sensors, nano-encapsulation, nanocomposites, food packaging, and nano-emulsions are discussed. Despite tremendous advancements in nanotechnology in food items, nanomaterials and nanoparticle toxicity are not fully understood. If the chemical mechanisms through which nanomaterials interact with food are not completely understood, we may face a nano-toxicity catastrophe, hence they must be further characterized and their usage must be carefully controlled.

INTRODUCTION

Nanotechnology is a multidisciplinary field that includes biotechnology, chemistry, engineering, and physics and implies the utilization of nano-materials with nanoscale structures ranging from 1-100 nm [1]. Nanotechnology provides interesting opportunities in the food industry, including quality control, food safety, as well as the development of new food flavors and additives [2]. Nanotechnology plays a vital role in the agriculture and food sector by manipulating nanomaterials for various purposes, including crop improvement, improving food safety and quality, and promoting human health using innovative methods [3]. Food spoilage can occur for numerous reasons, including spoilage due to pathogens and chemicals. In the food sector, food wastage results in significant losses. According to "Food and Agriculture Organization", above "1.3 billion metric tons" of edible food are wasted each year all over the supply chain, primarily due to inadequate post-harvest techniques, transportation, and storage facilities, as well as consumer and market food waste [4]. Nanotechnology is utilized in the food industry to create packages with improved mechanical or thermal properties and safety. Nano-sensors inserted in food packaging systems, are utilized to notify consumers when food has expired [5]. Various nanomaterials including Nano laminates, nano-clays, nanofibers, nano-emulsions, and nano-rods have been created to improve agricultural production and enhance food quality [6]. Nanomaterials are also employed to increase the protective features of food due to their unique capabilities. Furthermore, numerous nano-sensors and nano-packaging materials have been employed to boost sensitivity and specificity in detecting pesticides, microbial contamination, and

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hazardous substances. Food processing is further enhanced by nano-encapsulation, which allows for the release of bioactive chemicals, boosts food bioavailability, and extends food shelf life [7]. Nanotechnology has received attention from regulatory authorities such as FDA to improve food safety and quality. Regulatory authorities have proposed safety regulations and testing protocols for nanotechnology in food packaging and processing, although approaches differ by area [8]. This review discusses possible applications and utilization of nanotechnology using various nanomaterials in the food sector for better quality and shelf life through preservation, security, processing, and storage. The potential uses of nanotechnology in food pathogen detection, nutraceuticals, and possible negative impacts of nanotechnology on animal and human health are discussed.

Nanotechnology in Food Processing

Nano-emulsions

In the food sector, nano-emulsions are utilized to produce things like salad dressing, flavored oils, individualized drinks, sweeteners, and more [9]. Nano-emulsions are colloidal solutions that have oil-in-water emulsion properties, comprising small droplets (10–1000 nm) with lipophilic and amorphous surfaces [10]. The small size of nano-emulsions allows for the production or existence of a large surface area, which can be crucial for substantial interaction with a variety of bioactive chemicals absorbed in the digestive system. Moreover, nano-emulsions digest faster than traditional emulsions because they have more binding sites in the gastrointestinal tract for the enzymes amylase and lipase [11]. Because their properties, composition, and structure can be adjusted, the nano-emulsion-based approach effectively boosts the bioavailability of physiologically active compounds [12].

Nano-encapsulation

Nano-encapsulation involves packing substances into small structures through methods like nano-structuration, nanocomposites, or nano-emulsification to enable precise release of the core. Various forms of Nano-encapsulation, such as nanoparticles, Nano-spheres, and liposomes, are employed based on specific applications. These techniques find use in diverse areas, including the use of dietary supplements to mask unwanted flavors, facilitate the effective dispersion of insoluble supplements, and enhance the bioavailability, all without the need for surfactants or emulsifiers [13]. The application of nano-encapsulation has been employed to enhance the shelf life of tomatoes, and there is potential to extend this strategy for preserving other fruits and vegetables [14].

Nano-laminates

Nano-laminate films typically consist of two or more layers of manmade or natural polyelectrolytes mixed with nanoparticles (dendrimers, silica, or inorganic nanoparticles, etc.), connected through chemical or physical means. Layer-by-layer deposition is the most common synthesis technique, allowing the surface lamination of multiple nano-layers using various nanomaterials [15]. Various adsorbing compounds, such as charged lipids, bio-based or natural polyelectrolytes, and colloidal particles, can enhance the properties of different layers [20]. Additionally, active compounds like anti-browning agents, antioxidants, antimicrobials, enzymes, odors, and flavors can be incorporated into the films to prolong the shelf life and quality of packaged food products including sausages, vegetables, citrus fruits, and other meat products [16]. Nano-laminated coatings can also be produced from edible or bio-based ingredients, serving as edible nano-coated films [17].

Nanoparticles

At the Nanoscale, nanoparticles serve to enhance food's flow properties, color, and stability [18]. Nanoparticles containing plastic films as nanoparticles of silicate, titanium oxide, and zinc oxide serve to minimize the flow of oxygen inside the food containers helping to reduce moisture leakage by improving the shelf life of the food products [19]. Nanoparticles of Silicon dioxide are used as anticaking or drying agents in food packaging and help to absorb the molecules of water in food thus, showing hygroscopic applications [20]. Silver nanoparticles act as effective antibacterial as they can penetrate through biofilms, they also help in decomposing ethylene hence, improving the shelf life of various fruits as well as vegetables [21]. Other nanoparticles with antimicrobial activity are copper and its oxide, zinc oxide, magnesium oxide, selenium, cadmium, chitosan, telluride, and single-walled carbon nanotubes [22] (Table 1).

Table 1: Nanotechnology in Food Processing

Processing Techniques	Food Items	References
Nano-Emulsions	Fresh-Cut Pineapples, Chicken Breast Fillet, Lettuce, Milk	[23]
Nano-Encapsulation	Fruit Juices (e.g., Carrot, Grape, Pomegranate etc.)	[24]
Nano-Laminates	Meats, Fruits, Vegetables, Cheese, And Bakery Products	[25]
Nano-Particles	Apples, Meat	[12]

Nanotechnology in Food Packaging

Food packaging is crucial to ensure food safety as it is important to protect food from contamination and spoilage, enhance sensitivity by increasing the activity of enzymes, and minimize weight loss –26]. Using nanostructured and nano-modified materials for packaging is important to improve the shelf life of food products –27]. The applications of different nanoparticles in food packaging are briefly explained (Table 2).

Table 2: Applications of Nanoparticles in Packaging of Food

Nano-particles	Matrix	Applications	Reference
Silver	Poultry Meat, Orange Juice, Asparagus, Fresh Cut Melon, Beef and Meat Exudates	Stops aerobic psychotropic, molds, and yeast growth, has antimicrobial properties against Escherichia coli and Staphylococcus aureus	[28]
Zinc Oxide	Liquid Egg Albumen, Orange Juice	Without affecting quality it decreases the growth rate of Lactobacillus plant arum, yeasts, molds,and salmonella	[29]
Titanium Oxide	Strawberry, Chinese Jujube	Decrease browning rate, ripening as well as senescence and decaying process	[30]
Silver Oxide	Apple Slice	Slows-down microbial spoilage	[27]

The use of nanotechnology in packaging has shown a great number of commercial applications in recent years [31]. The advantages of using nanoparticles in food packaging include enzyme mobilization, antimicrobial potential, O2 transport, and clues for factors associated with degradation[32].

Active Food Packaging

Active packaging uses nanoparticles of metal and metal oxides as antimicrobials such as Silver (Ag) and TiO_2 [33]. Due to the semi-conducting properties of TiO_2, it is frequently used as an adsorbent material, strain, or catalytic substrate with increased optical, photosensitive, and electrical outcomes [34]. Active packaging keeps the food secure from environmental components by acting as a barrier to outside conditions[35].

Smart Packaging System

Nanoparticles inserted in smart packaging systems, are used to detect any chemical changes inside as well as outside the food by helping in tracing fraud. It improves mechanical barrier, and antimicrobial properties as well as monitors food during its transport and storage [36]. Various types of sensors such as chemical and biosensors are used in smart packaging systems to monitor the quality and protection of packaged goods like pharmaceuticals, foods, and health or household products [37]. Smart packaging is used to improve the total quality of food including Quality indicator (QI) temperature indicator (TI), gas concentration indicator (GC), and time-temperature indicator (TTI) provides more ease and protection against tempering of packages and counterfeiting, theft[38].

Improved Packaging

The uniqueness of improved food packaging is that nanoparticles are added to this packaging to enhance its physical and as well as mechanical properties including biodegradability, strength, UV absorptivity, strength, and oxygen permeability. Metal oxides are incorporated into the polymers that can enhance properties like light permeability [39]. Nano clay is also added because it enhances the properties of the barrier against UV radiations and gases [40]. Using one type of nano-coating allows only one benefit like enhancing the shelf life of food but applying a coating of different materials makes the food in multiple ways e.g. taste, smell, security, and ripening time[41].

Nano-clays

Nano clays are Nanoparticles that are made by layered mineral silicates, stacked together [42]. They are well-known for being reasonably priced nano-fillers that strengthen polymer nanocomposites and enhance their mechanical, thermal, and barrier qualities for use in food packaging [43]. Different types of nano clays are added to enhance the properties of polymers. Two types of Nano clays montmorillonite (MMT, MMT-Na+) and organophilic MMT (organic modified MMT, OMMT) are more prominent and preferred because of their high surface area, large aspect ratio (500-1000), and compatibility with organic thermoplastics[44].

Nano-cellulose

Nano-cellulose is synthesized by the breakdown of the cellulose particles, has the ability of biodegradability, and are biopolymer that produces the minimum amount of carbon prints [45]. Nano-cellulose can be prepared through a process of microbial fermentation or can be isolated from plant sources. Nano-cellulose has particular characteristics that enable it to be used for food packaging its crystallinity, length, diameter of the fiber, and polymerization ability enable it to work as a mechanical barrier and its degradability, renewability, and some morphological properties enable it to reinforce bio-based materials [46]. Plant cellulose is already used in food packaging as cellophane, paper board, or also in the form of modified cellulose that is hydroxyl-propyl cellulose (HPC), carboxy-methyl cellulose (CMC), and cellulose acetate, methylcellulose(MC).

Nanofibers

Nanofibers are fabricated by the method of electrospinning, within the range of micro and nanoscale [47]. Numerous materials like ceramics and polymers can be treated into nanofibers [48]. Nanofibers have outstanding properties of high porosity and large surface-to-volume ratio. In comparison to polymeric films of equivalent thickness, nanofiber mats exhibit superior mechanical capabilities. The latest research shows that nanofibers with antimicrobial activities are launched in the market that show applications in drug delivery, food packaging, and tissue engineering[49](Table 3).

Table 3: Nanotechnology Food Packaging Techniques Used for Different Foods

Processing Techniques	Examples of Food	References
Active Food Packaging	Meat, Fish	[50]
Smart Packaging	Milk, Shrimp, Chicken Breast	[39]

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Improved Packaging	Beer	[31]
Nano-clays	Meat, Bread, Fruits,Vegetables, Dried Fruits,Cheeses, Coffee	[52]
Nano-cellulose	Fruits, Vegetables	[53]
Nanofibers	Spinach, Melons, Mangoes	[54]

Methods of Nano-encapsulation

Several methodologies are used to bring about nano-encapsulation to attain enhanced bioavailability and deliver desired substances safely and in a controlled manner. A vehicle with such characteristics and benefits usually consists of a core protected by a polymer membrane layer[55].

Emulsification

Emulsification is used to prepare nano-capsules in which two immiscible liquids are mixed via the use of a surfactant (Tween 20, Tween 40, etc.). It results in the formation of nano-emulsions of two types based on oil and aqueous media resulting in the suspension of a water molecule in an oily media or vice versa. The preparation of nano-emulsions via low and high-energy methods produces droplet sizes ranging from 20-200 nm. However, low-energy methods are preferred since they are cost-effective and depend mostly on the system's internal chemical energy[56]. Sol-gel methodology focuses on the formation of gel structure with an inorganic network. Firstly, a solution is prepared (sol) and subjected to solidifying and heating to stir up the inorganic and organic molecules in the mixture. It results in forming a 3D network with high versatility and potential for incorporating functionalities [57].

Drying or Solvent Removal

This method mainly involves the removal of organic solvents like ethanol, methanol dichloromethane, etc. which can dissolve the polymer, which causes adverse effects in certain environmental conditions, to produce a powdered form of Nano capsule through Spray drying or Freeze drying. In the former, the atomizer disperses the liquid into a medium containing hot dry gas, resulting in solvent loss in a drying chamber. Freezing, however, relies on the sublimation of solvent from frozen to the gaseous state through surrounding temperature. The main problem in drying is losing original physio-chemical properties to some extent along with reduced product recovery[58]. The better technique, however, is spray drying since it operates with simple controls and provides cost-effective results [59].

Electro Hydrodynamic Processes

Electrospinning and electrospray are applicable in the production of Nano-microcapsules with high feasibility and potential. This process involves the ejection of liquid polymer solution that contains polyvinyl alcohol (PVA) or poly-capro-lactone (PCL) dissolved in organic solvents, through an atomic nozzle into an area that is controlled with varying electric fields allowing them to stretch immensely and solidify via cooling or evaporation, the resulting particles are collected in form of sheets[58]. The variation in electrospray from electrospinning stems from the varicose instability of finely charged molecules when the concentration of polymers is low. However, a rapid formation can be obtained through this strategy[60].

Nanotechnology in Food Safety

Food safety is a persistent health issue comprising foodborne diseases (FBD) due to insufficient food handling procedures, contaminated food supply, and inadequate cleanliness. Consumer sickness and FBDs are frequently connected, showing significant medical expenses, and decreased revenue and efficiency. To ensure food safety, advanced technologies such as the development of nano-sensors are utilized for the preservation and processing of food [61]. Nano-sensors can detect and provide signals for the assessment of the physical or chemical qualities of any particle that has contaminated food.

Radio Frequency Identification Sensors (RFID)

People nowadays want safer and healthier foods. To ensure food safety a complex and well-structured system RFID is developed [62]. RFID can detect any tangible object, it consists of a reader and a transponder. The reader is a device that emits radio waves in the form of an electromagnetic field [63]. This field provides energy for the radio tags to operate. The tag is a small device that is made up of an antenna and a microchip. The microchip and an antenna allow the tag to receive and transmit data[64]. RFID tags come in passive, semi-passive, and active forms [65]. RFID is mainly used to detect changes in food such as chemical changes, pH, humidity, temperature, and gas changes. The recorded changes are sent to the control system[66].

Gas Sensor

Foods that contain high levels of oxygen cause browning by food pigment oxidation and fat oxidation [67]. Most spoilage caused by bacteria and fungi needs oxygen to grow and these sensors measure oxygen content in the food. These sensors are made to detect gasses that come from the metabolism of microorganisms and are released when food spoils [68]. Gas sensors can be broadly categorized into two primary groups according to the type of transducer they use: electrochemical (potentiometric, amperometric, and conductor) and optical (colorimetric, gas-induced fluorescence change) [69]. Limit detection (LOD), power consumption, response and recovery durations, sensitivity, selectivity, and other parameters all play a part in how well these sensors perform in commercial applications [70]. The gas sensors are usually used to detect volatile organic compounds compromises of organic acids, esters, aliphatic alcohols, polyphenols, aldehydes, ketones, and amino acids[71].

Sensor for Food Pathogens and Contamination

Nanotechnology-based sensors are utilized to detect pathogens and contamination in food [72]. Nano-sensors have potential for quick pathogen detection because of

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their sensitivity, and specificity which are derived from antibody-antigen interaction [73]. Furthermore, because of their small size, nanomaterials can attach to bacterial cells, amplifying signals and extending detection limits. Commercially available sensors such as Toxin Guard and Food Sentinel Systems, are nano-sensors based on antigen-antibody interaction [74]. This detector uses thin polymer films with immobilized antibodies to detect pathogens that cause food-borne diseases. The change in configuration or color suggests the presence of pathogens [75].

Toxin Detection

Quantum dot sensors are used to detect the toxins and pesticides present in the food. Using water-soluble bi-conjugated QDs, toxins and enterotoxin (produced by S. aureus and E. coli) can be identified. The benefit of these artificially created aqueous QDs comprises extended photo stabilities, wide absorption, stability, and a highly compatible, highly specialized emission spectrum. Because of their unique optical and magnetic characteristics, they can be combined with various biomolecules to form hybrid, integrated biosensors with targeted, sensitive detection capabilities [76]. QDs can be assembled in an assembly and coated with a coating of chitosan, thio-glycolic acid, and organophosphorus hydrolase to detect the harmful chemical (paraoxon) produced by the organophosphorus insecticide parathion [77](Table 4).

Table 4: Nano-sensors Used for Safety Detection in Various Food Items

Nano-sensors	Food Items	References
RFID Sensors	Meat, Fruit, and Dairy Products	[53]
Gas Sensors	Chicken, Apples, Pears, and Kiwis	[71]
Food Sentinel Systems (Sensor for Food Pathogens and Contamination)	Fish, Poultry, Meat,	[74]
Quantum Dot Sensors	Milk, Egg, Chicken, Vegetables, Water	[78]

Nanotechnology for Detection of Mycotoxins in Food and Feed

About a million species in the fungal kingdom are used for different industrial activities, including manufacturing chemicals and antibiotics. By fermentation, fungi are also essential to the synthesis of food and drink [79]. On the other hand, more than 400 fungal species are harmful to people and can result in endemic or infectious diseases. When mycotoxin-producing fungi are found in poisoned food and feed, they may be extremely harmful to both human and animal health [80]. Aspergillus, Fusarium, and Penicillium are prominent fungal genera that produce mycotoxin; among these, aflatoxins, ochratoxin A, zearalenone, fumonisins, and trichothecenes are of particular concern because of their potential health and economic effects [81].

Mycotoxin Toxicity and Regulations

Mycotoxin exposure can have severe, life-threatening consequences in addition to harmful effects including damage to the DNA, oxidative stress, and cell death. The degree of toxicity can vary greatly. The International Agency for Research determines mycotoxin carcinogenicity in Cancer [82]. Mycotoxin maximum values in food and feed have been set by regulatory authorities such as the EU Scientific Committee for Food (SCF) and the World Health Organization (WHO) to protect public health. Effective detection techniques are required to ensure respect for these standards and minimize financial damages [83].

Challenges in Mycotoxin Detection and Conventional Methods

Mycotoxins have low concentrations (parts per billion) in food and feed, making detecting them in trace amounts difficult. Conventional techniques like enzyme-linked immunosorbent tests (ELISA) and the use of high-performance liquid chromatography (HPLC), although sensitive and specific, are time-consuming, costly, and take a lot of time [84]. In contrast, rapid screening tests are not as effective or reliable as they should be. Because of this, there is an increasing need for quick, affordable, and trustworthy methods for mycotoxin detection in quality food management [79].

Biosensors for Mycotoxin Identification

Biosensors are emerging as a valuable tool for the early detection of food spoilage, poisonous fungi, and mycotoxins. These devices combine a biological sensing element with a transducer to offer sensitivity, simplicity, and fast analysis [85]. There are many types of biosensors, including piezoelectric, optical, and electrochemical biosensors, which introduce nanomaterials to boost signal strength and sensitivity. For instance, gold nano-rods embedded in optical biosensors are used to detect aflatoxins, quantum dots are used for mycotoxin detection in food beverages, and silver nanoparticles for ochratoxin detection [86](Table 5).

Table 5: Nano-Biosensors for the Detection of Mycotoxins in Food

Nano-biosensors	Mycotoxin Detected	Food Item	References
Immuno-Chromato-Graphic Nano-Biosensors	Zearalenone (ZEN)	Corn	[86]
Fluoro-Immunoassay Nano-Biosensor	Aflatoxin B1	Peanuts	[86]
Electrochemical Biosensor (Aunps/COF/Apt)	Zearalenone (ZEN)	Corn Flour	[87]
Electrochemical Biosensor (Nafion/G/Aunps/Phno2/Ab)	Deoxyniva-lenol (DON)	Cereals	[87]
Electrochemical Immuno-Sensor	PAT	Apple Juice	[88]

Safety Concerns of Nanotechnology in Food Industry

Because of nanotechnology developments, nanoparticles' use in the food business is expanding, causing serious safety risks and regulatory difficulties. Risks related to nanoparticle usage in food items are receiving immediate

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attention due to limited knowledge of their toxicity and the release of allergens and heavy metals [89]. Nanoparticles have the potential to cause unexpected health hazards by interfering with biological processes, damaging DNA, and affecting different parts of the cell. Complete toxicity studies are necessary due to the possibility of organ accumulation and the wide range of effects that nanoparticles might have on various tissues [90]. Although organic nanoparticles are usually considered non-toxic, the lack of international rules and differences in regulatory strategies, such as those used by the FDA and EFSA, emphasize the necessity of uniform safety evaluations and precise recommendations. Achieving a balance between using nanotechnology's advantages in food processing and protecting human health requires thorough investigation, clear laws, and public participation in decision-making [91].

Safety Concerns

To ensure food safety, it is essential to address the potential for nanoparticles to migrate from packaging materials into food products. A thorough understanding of the functional properties and toxicity of nanomaterials at the nanoscale will greatly improve the practical applications and safety standards of nanotechnology. It is important to recognize and address the potential health risks, toxicity issues (organ and tissue toxicity), and environmental concerns associated with nanoparticles [92]. There has been a noticeable advancement in the use of innovative nanotechnology in the food sector, even though the possible toxicity of nanomaterials is still not fully known and the FDA has given general approval for the use of nanotechnology in the food industry. The FDA does not categorically ascertain products containing nanomaterials or utilizing nanotechnology as inherently safe or harmful. Instead, the FDA will regulate nanotechnology products within its existing statutory authorities, in line with the specific legal standards applicable to each type of product under its jurisdiction. The FDA supports innovation and the safe use of nanotechnology in FDA-regulated products through enhanced scientific expertise and tools necessary to assess the safety and effectiveness of products under balanced regulatory oversight [93].

CONCLUSIONS

It was concluded that nanotechnology provides multiple methods for improving food safety throughout the supply chain. These improvements, which range from nano-sensors to RFID devices, allow for the accurate detection and control of pollutants. Regulatory and safety concerns remain significant needing extensive toxicity assessments. Nonetheless, nanotechnology's ability to revolutionize food safety measures is apparent. FDA has given general approval for the use of nanotechnology techniques and nanoparticles in food packaging, processing, and preservation with proper safety assessments but there are still many health risks associated with the use of nanotechnology in the food industry. Continued research and collaboration are required to obtain the full benefits and protect consumer health in modern food systems.

Authors Contribution

Conceptualization: AJ
Methodology: AJ, SI, AA[1], MB, AA[2], SU
Formal analysis: MBS, MW
Writing review and editing: AJ, MW, MAH

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

All the authors declare no conflict of interest.

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