**Prospect of Nanotechnology in Food Packaging**

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**Introduction:**

In recent decades, nanotechnology has emerged as a groundbreaking technology in the food sector. Nanotechnology is the study of using particles that measure between 1-100nm to create materials with outstanding properties. The size of the nanometers facilitated the examination and handling of materials at the nanoscale. Nanomaterials have unique properties due to their high surface-to-volume ration and diverse characteristics. These unique physiochemical features set them apart (Gupta *et al.,* 2016). The economic revolution driven by nanotechnology has sparked global interest and investment. The implementation of nanotechnology has the potential to enhance food processing, resulting in better nutrient stability and increased bioavailabilty. Nanoparticles possess outstanding mesoscopic properties, including remarkable surface area, reactivity, strength, quantum effects, and ductility. They are extensively utilized innumerous industries (Omerović *et al.,* 2021). The field of science has benefited greatly from research on nanomaterials, including their synthesis, categorization, applications, and assessment. Nanomaterials have revolutionized the agri-food industry with their exceptional physicochemical and biological properties, enabling them to carry out diverse functions. Nanomaterials have proven to be valuable asset to the field of science, particularly in the realm of agri-food industry. Their unique properties have enabled them to effectively perform key function such as synthesis, categorization, applications, and assessment, ultimately transforming the industry (Bouwmeester *et al.,* 2018). Nanotechnology plays a crucial role in the detection of food-related illnesses, devising nutritional plans for the elderly, and ensuring sustainable food production through nanoencapsulation. Various food additives such as preservatives, flavoring agents, encapsulated food ingredients, antimicrobial sensor, packaging compounds, and nanoparticles are employed to enhance the nutritional value, aroma, texture, and shelf life of food products.

**Nanotechnology’s Role in Enhancing Food Packaging:**

Packaging plays a crucial role in safeguarding, systematizing, conveying, and identifying goods across the complete supply chain, starting from the initial materials to the final consumers (Figure 1). When it comes to packaging and preserving item, it is essential to take into account the mechanical, thermal, and barrier specification. These requirements are crucial to ensure that the items remain intact and protected throughout the packaging and transportation process.

**Figure 1: Functions of the Packaging**

Ensuring food safety heavily relies on appropriate packaging. It must be recognized that all packaging substances are susceptible to certain degree of penetration by natural elements, atmospheric gases, and water vapor. To ensure the preservation of fresh fruits and vegetables during cellular respiration, it is imperative to avoid any gas migration and permeability. For the preservation of carbonated beverages, it is imperative that the packaging is designed to obstruct the passage of oxygen and CO 2. The regulation of CO2, oxygen, and water vapor flow in food packaging can be effectively managed with the use of nanocomposite materials like polymers. Such materials possess the capability to tackle the numerous complexities that surface during this process (Abbaspour *et al.,* 2015). In order to prolong the shelf life of products, it is recommended that nanopackaging be created with the capability to release antimicrobials, antioxidants, enzymes, flavors, and nutraceuticals (Figure 2).

**Figure 2: Application of Nanotechnology in Food Packaging**

**Nanotechnology in Packaging**

Improved packaging

Nano-biosensors for pathogen detection

Improved packaging

Nanoparticles as antimicrobial agent

Improved packaging

Food’s physical performance is improved with the use of nanotechnology.

*Source*: Singh *et al.,* 2017

The majority of current food packaging materials are comprised of non-biodegradable plastic polymers derived from petroleum, which presents a significant environmental threat. Using bio-based packaging, like edible and biodegradable films made from renewable resources, is essential to reduce packaging waste and improve food quality by extending shelf life. This innovative approach has immense potential and must be implemented to achieve a significant and lasting improvement in our environment and food industry.

Nanoparticles are becoming increasingly prevalent in food packaging due to their enhanced functional capabilities. Presently, there are 500 nano-packaging items commercially available, and it is a fact. A recent study has revealed that within the next decade, 25% of all food packaging will be manufactured using nanotechnology (Reynolds. 2007). Nanotechnology is a highly effective method for increasing the longevity of products. By releasing antimicrobial, antioxidants, enzymes, flavors, and nutraceuticals, this technology ensures that product remain fresh and safe for use for an extended period of time.

The packaging industry overwhelmingly relies on non-biodegradable plastic polymers that are derived from petroleum, which pose a environmental threat. In particular, non-biodegradable food packaging materials have had a devastating impact on the planet (Kirwan and Strawbridge. 2003). The utilization of biodegradable packaging materials can be an effective solution to address this problem. Using bio-based packaging materials, like edible and biodegradable films made from renewable resources, can help reduce packaging waste and increase keeping quality of the food products. This may solve the waste problem and improve food quality.

# Bio-Based Packaging:

Bio-based packaging offers a safeguard against various environmental factors that could compromise the quality and freshness of food products. By creating a barrier that shields against bacterial growth, humidity, and gas conditions, this type of packaging effectively protects the contents within. Although biodegradable materials are the ideal option for packaging, they must be improved due to their poor mechanical and thermal resilience, low gas and water barrier properties. In order to surpass these constraints, biopolymer has been improved through the integration of nanofillers, resulting in the development of bio-nanocomposites (Sharma *et al.,* 2017). The nanoreinforceent of biopolymers has been done using nanofillers such as nanoclay and layered silicate nanoparticles (montmorillonite (MMT)) (Fortunati *et al.,* 2018). In order to increase the strength and viability of polymer packaging, nanoreinforcement involves filling the space between polymer molecules with nanofillers. Bio-based materials can be produced using renewable or non-renewable resources, and although some exhibit biodegradability, others do not.

In accordance with their soureces, bio-based polymers can be divided into three types:

1. Polymers produced from natural sources (proteins, polynucleotides, polysaccharides etc.)
2. Polymers produced from bio-monomers or chemical synthesis from bio based monomers (bio-polyesters, PLA,PBS,PVA,PGA (polyglycolic acid))
3. Polymers extracted from microorganisms or genetically modified organism (GMOs) (PHB, xantha, PHA (polyhydroxyalkonoates)) (Reddy *et al.,* 2013)

## Bionanocomposites:

Bio-nanocomposites, such as PLA, PHB, and PBS, among others, that are based on chitosan, proteins, cellulose, and starch have lately come under notice for their improved performance in food packaging. Antioxidants, oxygen scavengers, antibacterial activity, scent, color, and other biologically active substances may be added to bio-nanocomposites to increase biochemical packing and active functionalities.

### Natural bio-nanocomosites:

Sustainable packaging applications have acknowledged the potential of numerous natural polymers including starch, chitosan, cellulose, and proteins, along with naterials like nanoclay and zein. These polymers have been recognized for a number of uses in food packaging, which are thoroughly covered in the sections below.

**1.1 Starch based nanocomposites:**

The most popular polysaccharide used for biodegradable packaging is starch. It is a plentiful, affordable, recyclable, and environmentally beneficial polymer for packaging. However, starch-based polymers have several key limitations, including poor mechanical and barrier qualities, sensitivity to UV and moisture, and low durability (Flores *et al.,* 2007). Starch has been modified to have better mechanical and barrier qualities by adding nanoparticles like ZnO, TiO2, Graphene, and poly (methyl methacrylate-co-acrylamide).

The rle of starch and other bio-based nanocomposites in improving polymer properties is highlighted in table 1, which contains the latest reserach.

**Table 1: Starch based bionanocompsites for packaging and their application in food industry**.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Polymer matrix** | **Polymer source** | **Nanomaterial** | **Improved proerties** | **Refrences** |
| Starch | Cassava | Starch nanocrystals | Mechanica,watervapor permiability | Garcia *et al.,* 2009 |
| Starch | Corn | Poly vinyl chloride (PVA)loaded with anao size poly (methyl methacrylate- acrylamide) | Hydrophobicity | Yoon *et al.,* 2012 |
| Starch | Pea | Starch-PVA blend | Mechanical barrier | Cano *et al.,* 2015 |
| Starch | Potato | Starch nanocrystals | Mechanical thermal | Sessini *et al.,* 2016 |
| Starch | - | Starch/TiO2 nanocomposites | Thermal mechanical, hydrophobicity, water vapor permeability | Goudarzi *et al.,* 2017 |
| Starch & PVA | - | Nano TiO2 | Antimicrobial,mechnical, tensile strength | Liu *et al.,* 2015 |

**1.2 Chitosan based nanocomposites:**

Another natural polysaccharide, chitosan, is produced by deacetylating chitin, a plentiful biopolymer. It is a polymer that is both biocompatible and biodegradable and has antibacterial qualities. Biocompatible and biodegradable films, coatings, compostie materials, and nanocomposites have been produced using chitosan and chitosan-based systems (Wang *et al.,* 2018).

**Table 2: Chitosan based bionanocompsites for packaging and their application in food industry**.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Polymer matrix** | **Polymer source** | **Nanomaterial** | **Improved proerties** | **Refrences** |
| Chitosan | Marine sources | Chitin whiskers | Mechanical water vapor pemeability | Rubentheren *et al.,* 2015 |
| Cellulose micro/nano fibers | Mechnical transparency | Fernandes *et al.,* 2009 |
| BC micro/nano fibers | Mechnical, water vapor permeabilty, antibacterial | Fernandes *et al.,* 2009 |
| Cellulose nanocrystals (CNC) | Tensile strength, mechanical, water permeability | Khan *et al.,* 2012 |
| PVA-chitosan | Marine source | TiO2 NPS | Mechanical gas barrier | Lian *et al.,* 2016 |

**3.3 Cellulose based nanocomposites:**

The environment is abounding in cellulose, a natural polymer made of glucose monomers. Because pure cellulose lacked the desirable properties for packaging applications, cellulose derivatives like CNC (Cellulose nanocrystals) have been most frequently used as fillers for the reinforcement of polymer matrices (Brinchi *et al.,* 2013). Thus, CNC increased the polymeric matrix's mechanical, barrier, and thermal properties as a result (Duran *et al.,* 2011). As shown in Table 3, numerous nanocomposites have been created utilizing CNC and various metals/metal oxides (such as Fe3O4, TiO2, etc.), metal nanoparticles (such as Ag), MMT, and nanoclay to provide enhanced or modified packaging.

**Table 3: Cellulose based bionanocompsites for packaging and their application in food industry**.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Polymer matrix** | **Polymer source** | **Nanomaterial** | **Improved proerties** | **Refrences** |
| Cellulose | - | Surfactant modified CNC | Water permeability, oxygen barrier | Fortunati *et al.,* 2012 |
| Cellulose |  | PHBV-CNC-me (Functionalized methyl ester) | Mechanical, thermal, barrier, migration | Yu *et al.,* 2014 |
| Cellulose |  | Ag NPs, grapes seed extract (GSE), 2,6,6-tetranethylypiperidine-1-oxyly (TEMPO)-oxidised nano-cellulose (TNC) | Antimicrobial, antioxidant | Wu *et al.,* 2019 |
| Cellulose | Mango leaf | Nanobrillated cellulose films with mango leaf extract (NFC-MLE) | UV-light protection and antioxidant properties | Bastante *et al.,* 2021 |
| Carboxymethyl cellulose | - | ZnO NPs and grape seed extract (CMC/ZnO/GSE) | Water vapor and UV barrier, mechanical, antioxidant, extended the shelf-life of high-fat meats | Priyadarshi *et al.,* 2023 |

**3.4 Protein based nanocomposites:**

Bio-based packaging and bionanocomposite have been made using wheat gluten, lectins, corn zein, soy, and sunflower protein. Because they have weak mechanical and barrier qualities, protein-based packaging other than maize zein and keratin is less common. Consequently, plasticizers are typically utilized to enhance protein- based polymer matrices. Zein is a potential reinforcement agent because of its hydrophobic properties, and the Food and Drug Administration (FDA) has deemed it safe for packaging (Chuacharoen *et al.,* 2016).

**Table 4: Protein based bionanocompsites for packaging and their application in food industry**.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Polymer matrix** | **Polymer source** | **Nanomaterial** | **Improved proerties** | **Refrences** |
| Protein | Whey protein isolate (WPI) | Nanoclay | Mechnaical, water vapour permeability | Sothornvit *et al.,* 2009 |
| Soy protein isolate (SPI) | Exfoliate MMT (montmorillonite) | Mechniacl water vapor permeability | Kumar *et al.,* 2010 |
| Gelatin | Bacterial CNC | Mechanical, hydrophobicity | George *et al.,* 2012 |
| Whey protein isolate | Nanoclay | Mechanical, water vapor permeability | Sothornvit *et al.,* 2009 |
| Wheat gluten (WG) | Lignin NanoParticles (LNPs) | Uv resistance, water senstivity, mechnaical | Yang *et al.,* 2015 |
| Soyabean | ZnO | NPs | Tang *et al.,* 2019 |

**3.5 Nanoclay based nanocomposites:**

Since they are made of layered phyllosilicate clays, nanoclays, notably MMT, are widely employed as nanofiller. A material called nanoclay can greatly enhance the properties of polymeric matrices, including young’s modulus, elastic modulus, thermal stability, and barrier properties. Nanoclay can be added to polymeric materials through various methods, including in situ polymerization, melt intercalation, and solution intercalation. Several studies have shown that incorporating nanoclay into polymer matrices, such as polyactic acid (PLA) and ethylene vinyl alcohol (EVOH) improves the oxygen barrier and increases the shelf life of food. Due to the tortuous path of diffusion that clay reinforcement creates, nanoclay-based composites typically contain 5% weight-weight nanoclay particles, resulting in a drop in permeability of 80–90% (Cui *et al.,* 2015).

**2. Synthetic bio-nanocomposites:**

Since plastic usage has led to major health risks and environmental contamination, many researchers have been interested in bioplastics. Therefore, biodegradable or renewable polymers became popular as a replacement for plastic that was based on petroleum. Through the process of microbial activity, bioplastics and biopolymers have the ability to decompose into organic substances such as carbon dioxide, hydrogen, and water (Peelman *et al.,* 2013).

**Table 5 : Synthetic bio-nanocomposites** **and their use in bio-based packaging:**

|  |  |  |  |
| --- | --- | --- | --- |
| **Synthetic bio-nanocomposites** | **Polymer matrix** | **Nanomaterial/Nanoparticles (NPs)** | **Improved properties** |
| Polylactic acid (PLA) based nanocomposites | PLA (polylactic acid) | Ag-chitosan NPs | Antimicrobial |
| Nanoclay | Antibacterial |
| Cellulose nanowhiskers | Water vapor, oxygen barrier |
| Ag-zeolite NPs | Antimicrobial |
| Ag NPs | Antimicrobial |
| Polyhydroxyalkonoates (PHA) | PHBV (poly 3-hydroxybutyrate-co-3-hydroxyvalerate) | ZnO NPs | Mechanical, thermal, crystallization, antimicrobial |
| PHBV | Ag NPs | Antimicrobial |
| Mixed polymers | PLA/PCL (polcaprolactone) blend | Organomodified clay | Biodegradation rate, oxygen permeability, thermal, rheological |
| PLA-PHB blend | CNC and surfactant modified CNCs | Mechanical, film stretchability, oxygen and water barrier |

**Source:** Chausali *et al.,* 2022

**Conclusion:**

In food science and research, there have been enormous advancements in the use of nanotechnology. A more eco-friendly alternative to traditional plastic packaging is bio-based packaging, which is biodegradable and sustainable. A sustainable solution to the problems of persistent material degradation and plastic waste reduction is provided by the next generation of packaging. There are different types of biodegradable and biocompatible packaging materials that fall into four main categories. These categories include biopolymers derived from microorganisms or genetically modified organisms such as PHA, PHB, PHBV, and xanthan. Another category is synthetic biopolymers such as bio-polyesters, PVA, PBS, PLA, PGA, and others. Natural biopolymers such as polysaccharides, polynucletides, protein, and other fall into a third category. Lastly there are biopolymers that are made from a combination of these substances. Therefore, in order to achieve the desired qualities of an ideal packaging, substantial research and development is needed for the upgrading of bio-based packaging materials.

**References:**

1. Abbaspour, A., Norouz-Sarvestani, F., Noori, A., & Soltani, N. (2015). Aptamer-conjugated silver nanoparticles for electrochemical dual-aptamer-based sandwich detection of staphylococcus aureus. *Biosensors and Bioelectronics*, *68*, 149-155.
2. Bastante, C. C., Silva, N. H., Cardoso, L. C., Serrano, C. M., de la Ossa, E. J. M., Freire, C. S., & Vilela, C. (2021). Biobased films of nanocellulose and mango leaf extract for active food packaging: Supercritical impregnation versus solvent casting. *Food Hydrocolloids*, *117*, 106709.
3. Bott J., Störmer A., Franz R. *Chemistry of Food, Food Supplements, and Food Contact Materials: from Production to Plate.* ACS Publications; 2014. A comprehensive study into the migration potential of nano silver particles from food contact polyolefins; pp. 51–70.
4. Bouwmeester, H., van der Zande, M., & Jepson, M. A. (2018). Effects of food‐borne nanomaterials on gastrointestinal tissues and microbiota. *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology*, *10*(1), e1481.
5. Brinchi, L., Cotana, F., Fortunati, E., & Kenny, J. M. (2013). Production of nanocrystalline cellulose from lignocellulosic biomass: technology and applications. *Carbohydrate polymers*, *94*(1), 154-169.
6. Cano, A., Fortunati, E., Cháfer, M., González-Martínez, C., Chiralt, A., & Kenny, J. M. (2015). Effect of cellulose nanocrystals on the properties of pea starch–poly (vinyl alcohol) blend films. *Journal of Materials Science*, *50*, 6979-6992.
7. Chausali, N., Saxena, J., & Prasad, R. (2022). Recent trends in nanotechnology applications of bio-based packaging. *Journal of Agriculture and Food Research*, *7*, 100257.
8. Chuacharoen, T., & Sabliov, C. M. (2016). Stability and controlled release of lutein loaded in zein nanoparticles with and without lecithin and pluronic F127 surfactants. *Colloids and surfaces A: Physicochemical and engineering aspects*, *503*, 11-18.
9. Cui, Y., Kumar, S., Kona, B. R., & van Houcke, D. (2015). Gas barrier properties of polymer/clay nanocomposites. *Rsc Advances*, *5*(78), 63669-63690.
10. Duran, N., Lemes, A. P., Duran, M., Freer, J., & Baeza, J. (2011). A minireview of cellulose nanocrystals and its potential integration as co-product in bioethanol production. *Journal of the Chilean Chemical Society*, *56*(2), 672-677.
11. Fernandes, S. C., Oliveira, L., Freire, C. S., Silvestre, A. J., Neto, C. P., Gandini, A., & Desbriéres, J. (2009). Novel transparent nanocomposite films based on chitosan and bacterial cellulose. *Green Chemistry*, *11*(12), 2023-2029.
12. Flores, S., Famá, L., Rojas, A. M., Goyanes, S., & Gerschenson, L. (2007). Physical properties of tapioca-starch edible films: Influence of filmmaking and potassium sorbate. *Food Research International*, *40*(2), 257-265.
13. Fortunati, E., Luzi, F., Yang, W., Kenny, J. M., Torre, L., & Puglia, D. (2018). Bio-based nanocomposites in food packaging. *Nanomaterials for food packaging*, 71-110.
14. García, N. L., Ribba, L., Dufresne, A., Aranguren, M. I., & Goyanes, S. (2009). Physico‐mechanical properties of biodegradable starch nanocomposites. *Macromolecular Materials and Engineering*, *294*(3), 169-177.
15. George, J. (2012). High performance edible nanocomposite films containing bacterial cellulose nanocrystals. *Carbohydrate Polymers*, *87*(3), 2031-2037.
16. Goudarzi, V., Shahabi-Ghahfarrokhi, I., & Babaei-Ghazvini, A. (2017). Preparation of ecofriendly UV-protective food packaging material by starch/TiO2 bio-nanocomposite: Characterization. *International journal of biological macromolecules*, *95*, 306-313.
17. Gupta, A., Eral, H. B., Hatton, T. A., & Doyle, P. S. (2016). Nanoemulsions: formation, properties and applications. *Soft matter*, *12*(11), 2826-2841.
18. Khan, A., Khan, R. A., Salmieri, S., Le Tien, C., Riedl, B., Bouchard, J., ... & Lacroix, M. (2012). Mechanical and barrier properties of nanocrystalline cellulose reinforced chitosan based nanocomposite films. *Carbohydrate polymers*, *90*(4), 1601-1608.
19. Kirwan, M. J., & Strawbridge, J. W. (2003). Plastics in food packaging. *Food packaging technology*, *1*, 174-240.
20. Kumar, P., Sandeep, K. P., Alavi, S., Truong, V. D., & Gorga, R. E. (2010). Preparation and characterization of bio-nanocomposite films based on soy protein isolate and montmorillonite using melt extrusion. *Journal of food engineering*, *100*(3), 480-489.
21. Lian, Z., Zhang, Y., & Zhao, Y. (2016). Nano-TiO2 particles and high hydrostatic pressure treatment for improving functionality of polyvinyl alcohol and chitosan composite films and nano-TiO2 migration from film matrix in food simulants. *Innovative food science & emerging technologies*, *33*, 145-153.
22. Liu, C., Xiong, H., Chen, X., Lin, S., & Tu, Y. (2015). Effects of nano‐tio2 on the performance of high‐amylose starch based antibacterial films. *Journal of Applied Polymer Science*, *132*(32).
23. Omerović, N., Djisalov, M., Živojević, K., Mladenović, M., Vunduk, J., Milenković, I., & Vidić, J. (2021). Antimicrobial nanoparticles and biodegradable polymer composites for active food packaging applications. *Comprehensive Reviews in Food Science and Food Safety*, *20*(3), 2428-2454.
24. Peelman, N., Ragaert, P., De Meulenaer, B., Adons, D., Peeters, R., Cardon, L., ... & Devlieghere, F. (2013). Application of bioplastics for food packaging. *Trends in Food Science & Technology*, *32*(2), 128-141.
25. Priyadarshi, R., Kim, S. M., & Rhim, J. W. (2021). Carboxymethyl cellulose-based multifunctional film combined with zinc oxide nanoparticles and grape seed extract for the preservation of high-fat meat products. *Sustainable Materials and Technologies*, *29*, e00325.
26. Reddy, M. M., Vivekanandhan, S., Misra, M., Bhatia, S. K., & Mohanty, A. K. (2013). Biobased plastics and bionanocomposites: Current status and future opportunities. *Progress in polymer science*, *38*(10-11), 1653-1689.
27. Reynolds, G. (2007). FDA recommends nanotechnology research, but not labelling. FoodProductionDaily. com News 26 July 2007.
28. Rubentheren, V., Ward, T. A., Chee, C. Y., & Tang, C. K. (2015). Processing and analysis of chitosan nanocomposites reinforced with chitin whiskers and tannic acid as a crosslinker. *Carbohydrate polymers*, *115*, 379-387.
29. Sharma, C., Dhiman, R., Rokana, N., & Panwar, H. (2017). Nanotechnology: an untapped resource for food packaging. *Frontiers in microbiology*, *8*, 1735.
30. Singh, T., Shukla, S., Kumar, P., Wahla, V., Bajpai, V. K., & Rather, I. A. (2017). Application of Nanotechnology in Food Science: Perception and Overview. *Frontiers in Microbiology*, *8*, 268461.
31. Sothornvit, R., Rhim, J. W., & Hong, S. I. (2009). Effect of nano-clay type on the physical and antimicrobial properties of whey protein isolate/clay composite films. *Journal of Food Engineering*, *91*(3), 468-473.
32. Sothornvit, R., Rhim, J. W., & Hong, S. I. (2009). Effect of nano-clay type on the physical and antimicrobial properties of whey protein isolate/clay composite films. *Journal of Food Engineering*, *91*(3), 468-473.
33. Tang, S., Wang, Z., Li, W., Li, M., Deng, Q., Wang, Y., ... & Chu, P. K. (2019). Ecofriendly and biodegradable soybean protein isolate films incorporated with ZnO nanoparticles for food packaging. *ACS Applied Bio Materials*, *2*(5), 2202-2207.
34. Wu, Z., Deng, W., Luo, J., & Deng, D. (2019). Multifunctional nano-cellulose composite films with grape seed extracts and immobilized silver nanoparticles. *Carbohydrate polymers*, *205*, 447-455.
35. Yang, W., Kenny, J. M., & Puglia, D. (2015). Structure and properties of biodegradable wheat gluten bionanocomposites containing lignin nanoparticles. *Industrial Crops and Products*, *74*, 348-356.
36. Yoon, S. D., Park, M. H., & Byun, H. S. (2012). Mechanical and water barrier properties of starch/PVA composite films by adding nano-sized poly (methyl methacrylate-co-acrylamide) particles. *Carbohydrate polymers*, *87*(1), 676-686.
37. Yu, H., Yan, C., & Yao, J. (2014). Fully biodegradable food packaging materials based on functionalized cellulose nanocrystals/poly (3-hydroxybutyrate-co-3-hydroxyvalerate) nanocomposites. *Rsc Advances*, *4*(104), 59792-59802.