Sustainable Fruit Preservation: ZnO Nanoparticles and Glutinous Rice Starch for Extended Mango Shelf Life

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Abstract. Mango is one of the most economically essential fruits facing storage and transportation issues during long-distance markets due to its decomposable characteristics. Proofs suggest that the application of edible coatings reduces the loss of perishable commodities. The present study employed zinc oxide nanoparticles (ZnO NPs) at varying concentrations (0, 0.5, 1.0, 1.5, and 2.0 M) and glutinous rice starch as nanocoating. The application of the edible coatings significantly reduced physiological weight loss (%), total soluble solids (ºBrix), titratable acidity (%), pH, and disease incidence (%), which prolonged the shelf life of the fruits, demonstrating potential in maintaining fruit quality. The 1.5 M ZnO NPs- GRS recorded the most effective treatment on all parameters assessed.

Keywords: Glutinous Rice Starch, Nanocoating, Preservation, Shelf Life, Zinc Oxide Nanoparticles.

1.0 Introduction

Mango (*Mangifera indica L.*) is a tropical organic product planted in over 90 nations globally, generating more than 28.51 million tons of yield [1]. Mango fruits exhibit a distinct flavor and attractive aroma while also being rich in carbohydrates, proteins, lipids, minerals, and many nutrients, notably vitamins A (beta carotene), B1, B2, and C (ascorbic acid) [1]. Moreover, the fruit is rich in bioactive compounds, including cancer prevention agents that decrease the hazards and slow the maturing of specific types of malignant growths, improve lung functions, and diminish diabetics-related complications [1]. Nonetheless, marketed mangoes require high quality, especially in

R. Ramli and M. Zakaria (eds.), *Proceedings of the International Conference on Science Technology and Social Sciences – Physics, Material and Industrial Technology (ICONSTAS-PMIT 2023)*, Advances in Engineering Research 238,
https://doi.org/10.2991/978-94-6463-500-3_15

the international market [2]. Consequently, for interested countries to be more competitive, technology is essential to guarantee and extend the quality and shelf life of the fruit post-harvest [3].

Mango fruits have a limited post-harvest life at room temperature, ranging between 6–10 days and up to 14 days at low temperatures [4, 5]. The primary factors limiting the distribution and commercialization of mango are its susceptibility to cold injuries and post-harvest diseases, damaging the agriculture and trade industry. Furthermore, the high perishability of the fruit from physiological deterioration due to ripening, which results in water loss, wrinkling, and wilting, considerably affects the fruit's commercial value [6].

The shelf-life of mangoes is the time they can be stored or maintained before spoilage, decay, or loss of freshness. The quality of mangoes is crucial for economic value and availability, encompassing sensory characteristics like taste, aroma, color, texture, safety, nutritional value, and the absence of flaws or microbiological contamination. High-quality mangoes maintain desirable sensory properties, nutritional value, and safety throughout their shelf-life, making them a valuable choice for consumers and the food sector. Mechanical properties, thermal properties, and moisture barriers all play a crucial role in the structural integrity and shelf-life of mangoes. Firmness and resilience affect the susceptibility of the fruit to damage and bruising, while temperature affects its ability to endure temperature variations. Moisture barrier is essential for regulating moisture content, preventing dehydration, and preserving texture, flavor, and nutritional content [7, 8].

The physicochemical characteristics of mango cultivars exhibit considerable variation globally, owing to diverse factors, including maturity and ripening stage, cultivar type, cultivation practices, climatic conditions, harvest ripeness, and post-harvest storage and treatment [9]. The assessment of physiochemical characteristics and sensory profiles of different mango varieties holds significant importance in determining the quality factors contributing to the successful exportation of mangoes in a fiercely competitive global market. Extensive research has been conducted on quality attributes in nearly all prominent mango-producing nations across the globe [9]. The primary physicochemical studies encompassed in this study comprise texture analysis, moisture content determination, total soluble solids (TSS) measurement, acidity assessment, pH level determination, color analysis, chemical composition analysis, microbiological analysis, sensory evaluation, and disease incidence examination.

Currently, plastic films exhibiting selective permeability to carbon dioxide (CO2) and oxygen (O2) gases are being used to prolong the shelf life of fruits. The materials produce a modified atmosphere surrounding the fruits, decreasing O2 concentration while increasing CO2 availability [10]. Previous investigations demonstrated respiration rate reduction and delayed maturation in fruits wrapped with the films [11]. Polyethylene, polypropylene, and various polymers are commonly employed [12]. Nonetheless, environmental reasons arising from current consumer market trends resulted in the engagement of more nature-friendly materials by the food industry.

Edible films and coverings are manufactured from various materials, typically polysaccharides (such as cellulose, starches and derivatives, and vegetable or microbial gum), proteins (for example, gelatin, zein, and gluten), and lipids (waxes and lipid derivatives) [13, 14]. However, edible films now available in the market, made from commonly used biodegradable materials, are limited in their mechanical properties and ability to prevent moisture compared to synthetic polymers [15].

Starch, being the main carbohydrate stored in plants, plays an essential role in establishing the quality of food products. Additionally, this polymer holds significant importance and has been widely utilized in various applications, including both food and non-food sectors [16] (Egharevba, 2019). The polymer is often obtained from a natural source, which is abundant, cost-effective, and commonly consumed and digestive by animals and other living organisms. According to Surendren et al. [17], the functions of the most widely researched biopolymers, such as starch, its renewability [18], abundance [19], biodegradability [18] and high availability. Moreover, it comes from a wide variety of global sources such as barley [17], corn (Lauer et al., 2021), potato [17], wheat [17, 21], tapioca [17] and rice [17]. Corn, potato, rice, tapioca, and wheat are widely recognized as the primary source of commercially manufactured starches in the market [17]. These starches have been classified as gluten-free starches, making them suitable for individuals with gluten allergies. Therefore, the use of starch as a primary raw material in the food industry is significant.

Rice starch derived from *Oryza Sative L.*, consists primarily of branching amylopectin (70-80%) and linear amylose (20-30%) [22]. It is commonly consumed in the cooked rice form. In the region of Maluku, located in Indonesia, the annual rice output can only fulfill approximately 40% of the total demand from consumers [23]. The prevalence of starch in rice is attributed to its status as one of the most significant food crops extensively consumed in Asian nations such as Malaysia, Indonesia and Thailand [24]. A recent study has indicated that both the food and non-food industries are currently experiencing advantages derived from the versatile nature of rice starches [25]. Various regions yield distinct flavors and a wide range of rice varieties. The two most popular rice varieties in Pakistan are Irri and Basmati [11]. In Malaysia, consumers exhibit a significant level of awareness of Basmathi rice, which is imported from Pakistan, due to its distinctive aroma and exceptional quality. This argument has been supported by a recent research study, whereby it was discovered that Basmathi rice demands a more expensive rate in the market due to its enhanced more aromas, while Irri rice is comparatively more affordable owing to its non-aromatic properties [26, 27]. It can be assumed that rice is a primary dietary staple in the Southeast region [24].

Consequently, zinc oxide (ZnO) nanoparticles (NPs) are utilized as fillers. The ZnO NPs demonstrated antibacterial, anticorrosive, antifungal, and ultraviolet (UV) properties as well as the ability to break down ethylene and control ethylene production [28]. Moreover, ZnO NPs are not harmful to humans [28]. Accordingly, the present study aimed to inhibit post-harvest diseases on mango fruits by coating them with zinc oxide- glutinous rice starch (ZnO-GRS) solutions at different concentrations.

Furthermore, the current study aspired to enhance the mechanical and thermal properties as well as the moisture barrier of the thin film.

2.0 Methodology

2.1 Experimental Materials Collection

Uniform in appearance, size, and maturity waterlily mangoes purchased from local stores were employed in the current study. Moreover, only fruits that were free of pests, diseases, injuries, bruises, and blemishes were chosen. The mangoes were then cleaned with distilled water and dried at room temperature.

2.2 Preparation of ZnO NPs and Glutinous Rice Starch (GRS)

Commercially available 99% purity ZnO nano powder under 100 nm was processed in zirconia containers with zirconia balls at a 14 ball-to-powder weight proportion [29]. The mechanical processing was performed in an even ball factory at 500 rpm for 30 minutes [29]. Similarly, the commercially bought glutinous rice starch (GRS) was milled to acquire nanoparticle-sized flour.

2.3 Preparation of ZnO NPs with an Edible Coating Solution

The starch solution was prepared by dissolving 13.5 g of GRS in 500 ml of distilled water. Subsequently, 50 ml of ZnO NPs at 0.5, 1.0, 1.5, and 2.0 M were added to the GRS solution [29]. The solution was continuously stirred at 100˚C for 2 h [29]. The uncoated mango fruits were considered as control. The selected fresh mango fruits were dipped in solutions for coating with different concentrations of ZnO NPs. The treated and untreated (control) samples were kept in cartons at 27°C and 65 percent relative humidity for quality and shelf-life assessments [29].

2.4 Data Collection. During the study, random mangoes were selected from each experimental unit and the data per replication was recorded at two-day intervals for seven days. The fruits were assessed on the parameters below.

2.5 Weight Loss Percentage

The mangoes in the present study were marked prior to coating treatment. Each fruit was then weighed at regular intervals with a digital balance to determine weight loss during storage [29]. The weight loss percentage was calculated according to Equation 1.

$$\text{Weight Loss} = \frac{\text{Initial Mass} - \text{Final Mass}}{\text{Final Mass}} \times 100 \quad (1)$$

2.6 Disease Incidence and Severity

Mangoes must be checked every two days for anthracnose infection, according to [30, 29, 31]. In the current study, the disease incidence percentage was determined based on Equation 2. Concurrently, the severity of the infection was evaluated according to the index demonstrated in Figure 1.

$$\text{Disease Incidence (\%)} = \frac{\text{Black Spot Covered Area}}{\text{Whole Mango Fruit Area}} \times 100 \quad (2)$$

2.7 Moisture Content (MC)

In the present study, moisture content (MC) was assessed by measuring the mass of water molecules in a known mass of mango fruit. The MC was determined based on weight loss, measured post-24-hour calcination of the samples in a chamber furnace [29]. The calcination step was necessary to acquire an accurate mass of water molecules in the mangoes. The MC of each mango was calculated according to Equation 3.

$$\text{MC (\%)} = \frac{\text{Initial Weight} - \text{Final Weight}}{\text{Initial Weight}} \times 100 \quad (3)$$

2.8 Total Soluble Solids (TSS)

The total soluble solids (TSS) content of the fruits in the present study was determined with a hand refractometer. Initially, 10 grams of mango flesh was sliced and homogenised with 100 mL of distilled water utilising a blender [29]. Subsequently, the resultant mixture undergo filtration to eliminate the pulp. Following that, a small amount of the specimen was carefully applied onto the glass prism of the refractometer in order to acquire the immediate measurement [29]. The prism got a cleaning process using distilled water and was subsequently dried using tissue paper in preparation for the subsequent measurements. The results were expressed in ^{o}Brix.

2.9 Titratable Acidity and pH

Titratable acidity (TA) of the mangoes in the current study was expressed as the percentage of citric acid in fresh tissue. The acidity was determined according to the standard methods [1, 32]. Next, a volume of 100 mL of the filtrate was combined with a small quantity of phenolphthalein (1%), serving as an indicator. This mixture was then subjected to titration using a solution of 0.1 M NaOH until reaching the endpoint, which was identified by the appearance of a pink color change at a pH of 8.2 [29]. The remaining juice were used for the pH test. The pH of a fruit juice, which is

the equilibrium of hydrogen ions in the juice, was evaluated with a standard calibrated pH meter [29].

2.10 Characterization Techniques

2.10.1 Field Emission Scanning Electron Microscope (FESEM). In the current study, the surface characteristics and thickness of the ZnO films were determined with a field-emission scanning electron microscope (FESEM) (FEI Quanta 250 FESEM, Netherlands) set at 10 kV voltage. Thin sample films were employed since the instrument could only examine dried samples in either a thin film or powder form. In this analysis, the samples were in the form of thin films. The experimental sample consists of dried mango peels acquired from mango fruits. The mango peel is carefully extracted from the fruit, subjected to a controlled drying process until it reaches a predetermined moisture level, and thereafter employed for the studies. The drying process is carried out following standard procedures to achieve homogeneity and regularity in the peel samples. In order to determine the impact of varying concentrations of coatings on the post-harvest quality of mango peel samples, the preservation of these samples was obtained. This approach ensures that the initial state of the peel, encompassing its moisture content and freshness, is uniform throughout every sample. The samples were also coated with 99.9% gold to increase the conductivity of the mango peels prior to analysis.

2.10.2 X-ray Diffraction (XRD). X-ray diffraction (XRD) is a flexible and non-destructive method of identifying and qualitatively determining various crystalline and amorphous materials. In the current study, thin film samples were placed on the sample holder before subjecting them for XRD analysis. The dried sample exhibited the same features to the FESEM sample.

2.10.3 Fourier-Transform Infrared (FTIR). In the present study, Fourier-transform infrared (FTIR) spectroscopy was employed to establish the chemical structures, functional groups, and possible interactions between the components of the samples. The coated and uncoated mango sample films were analysed with a Frontier (FTIR) spectrometer [PerkinElmer, United States of America (USA)] within the 4000– 600 cm^{-1} spectral range. The dried sample exhibited the same features to the FESEM sample.

2.10.4 High Performance Liquid Chromatography (HPLC). The quantification of citric acid in mango was conducted using reversed-phase high- performance liquid chromatography (RP-HPLC). The sample was created using freshly extracted mango juice. The prepared sample was introduced into a reversed-phase high-performance liquid chromatography (RP-HPLC) system through injection with a volume of 20 microliters. The RP- HPLC system utilized in this study was outfitted with an analytical

column, namely the Synergi 4u Hydro-RP 80A column. Additionally, a diode array detector (DAD) was employed to detect and measure the analytes. The mobile phase employed in this analysis consisted of a phosphate buffer.

The citric acid standard solution was constructed by procuring citric acid from Sigma Aldrich and subsequently dissolving it in a suitable solvent. Various concentrations of citric acid (2000, 1000, 750, and 500 ppm) were generated to establish a standard calibration curve, which exhibited an r-square value of 0.99%. The citric acid content in mango was measured by employing a citric acid standard solution.

3.0 Result and Discussion

3.1 Disease Incidence

Table 1 exhibits the appearance of the uncoated mango (control) and mangoes coated with different concentrations of ZnO NPs (0.5, 1.0, 1.5, and 2.0 M). During the seven days of storage at room temperature, fungal growth on the control mango was observed on day 2 with an increasing percentage of severity compared to the coated mangoes. Conversely, the mango coated with 1.5 M ZnO-GRS only exhibited black spots of fungal growth on day 6. Due to its antimicrobial properties, the ZnO NPs could retard diseases on mango fruits.

Table 2 lists the disease incidence percentages of the mango samples observed in the current study. The data were obtained by calculating the area covered with black spots on the surfaces of mangoes. On day 7, the disease incidence percentage of the uncoated mango was 9.356%, while the ZnO NPs-coated samples exhibited 0%. *Collectrotrichum gloeosporioides* is the fungus responsible for anthracnose disease, one of the significant diseases infecting tropical fruits. Previous studies reveal that an elevated concentration of zinc oxide nanoparticles (ZnO NPs) coating has been found to enhance the beneficial impacts on the physiochemical properties of mango fruits [33, 34]. Similarly, the findings of the present study demonstrated that the antimicrobial capabilities of ZnO NPs effectively inhibited fungal growth on mango fruits.

Table 1. The observation of the control mango and the mangoes coated with various ZnO NPs concentrations.

Sample	Day 0	Day 2	Day 4	Day 6	Day 7
Control					

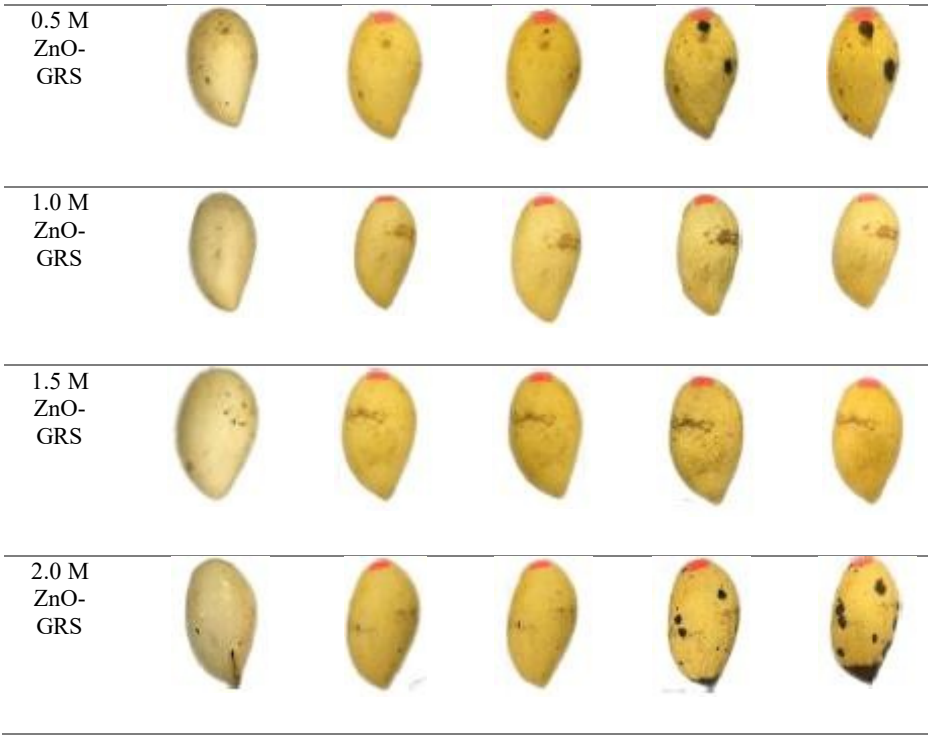

Table 2. The disease incidence percentage of the control and coated samples.

Sample	Disease incidence (%)
Control	9.356
0.5 M ZnO-GRS	4.084
1.0 M ZnO-GRS	0
1.5 M ZnO-GRS	0
2.0 M ZnO-GRS	8.998

3.2 Weight Loss

The shelf life and quality of mango fruits are primarily determined by weight reduction, which is caused by the loss of water through respiration and transpiration processes [35]. The shelf life and quality of mango fruits are primarily determined by weight reduction, which is caused by the loss of water through respiration and transpiration processes [35]. The deteriorating effects of weight loss extend beyond financial loss and include a reduction in water content, leading to undesirable changes such as the shrinking of the fruit's outer layer and a decline in nutritional quality [35]. Moreover, there is a significant correlation between water loss and several metabolic

processes that occur during post-harvest and throughout storage. Multiple studies have demonstrated the significance of respiration rate in the process of weight reduction [36, 36]. Moreover, weight reduction sometimes leads to a decrease in the sugar content and other elements of the fruit, thereby affecting its nutritional value. As a result, weight loss is evaluated to assess any MC reduction in the fruits. Moisture loss is driven by the water vapor pressure distinction between the fruit surface and the surroundings [37, 38].

The ZnO-GRS NPs coating employed in the present study notably impacted the weight loss of mango fruits during the storage week (see Figure 1), where the control and coated samples recorded reduced weight loss. The mangoes coated with 0.5 M showed the greatest weight reduction, while those coated with 1.5 M documented the least weight loss. The results of this study align with previous research conducted by other researchers, which indicated that the application of ZnO nanoparticle coating led to a reduction in weight loss in strawberries, apricots, and fresh-cut kiwifruits [39]. The antifungal action of ZnO is believed to be due to the production of reactive oxygen species (ROS) within the fungal cell wall when in direct contact with the nanobiocomposite [40]. The produced ROS induces heightened stress, resulting in oxidative damage to the fungal cell wall and cellular constituents. Prior studies indicated that the antifungal properties of ZnO nanoparticles were facilitated by the generation of ROS [41, 42, 43]. The ZnO and starch exhibit a synergistic or complementary impact, effectively combating other pathogenic microbes through their combined interactions.

A recent study reported that weight reduction in fruits is primarily due to high storage temperatures, skin expulsion and cutting that exposed interior tissues, hence elevating the water evaporation rate [44]. The results of the present study indicated that the ZnO NPs coating decelerated the weight loss of the mango fruits throughout the storage period. The reduced moisture loss rate was possibly due to the ZnO barrier properties against moisture diffusion through the stomata. The results were supported by investigations performed on mango [29, 45], guava [46, 47], litchi [45], longan [45], strawberry [39, 48, 49] and papaya [50].

In the current study, the mango fruits coated with 1.5 M ZnO-GRS documented reduced weight loss and the highest moisture content (MC). The MC represented the moisture-holding limit of the coating films. Furthermore, the limit influenced the functional properties of the coating, such as mechanical properties and water vapor permeability, which is a significant property. In another report, increased starch concentration also improved the MC of the samples observed [27].

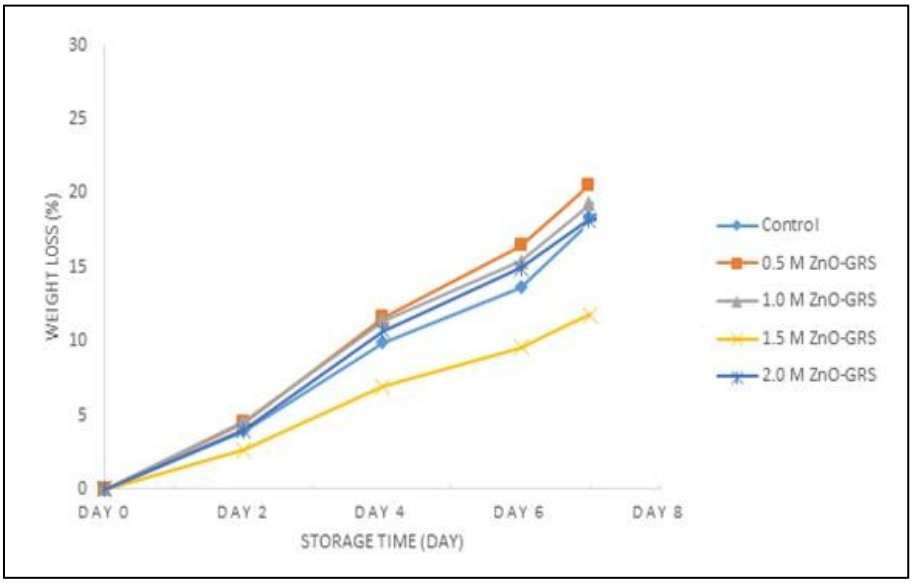

Fig. 1. The weight loss percentage of the control and samples coated with different ZnO-GRS NPs concentration after a week of storage.

3.3 Storage Quality

One of the critical measurements of mango fruit quality is its pH. Fruits with pH 2.5–6.0 typically possess prolonged shelf life as the multiplication of microorganisms is inhibited. During the storage period, the pH of the pulp of the fruits was seen to be lower when coated with an edible coating (see Table 3). This phenomenon can be attributed to the impact of the coating, which impeded the ripening process, resulting in the accumulation of organic acids [51]. The different concentrations of ZnO NPs coatings did not affect the pH of mango fruits throughout the storage period of the present study. Similarly, an investigation documented that the chitosan coating did not affect the pH of mangoes stored at 6ºC for seven days [52]. Different percentages of chitosan coating, 1–1.5%, also did not affect the pH of strawberries during storage [53].

As mangoes continue to ripen, the total soluble solids (TSS) content escalates, and sugar is one of the significant soluble solid components when the fruit is ripe. In the current study, the TSS of the coated and control samples increased with an extended storage period. Nevertheless, the TSS of the control climbed at a higher rate than the ZnO-GRS-coated mangoes.

During ripening, the TSS of a fruit increase, resulting in starch hydrolysis and pectin degradation. According to Dubey et al. [28], adding an increased concentration of NPs solution and aloe vera aided in maintaining a low TSS of the fruit, as it would have lowered respiration due to the oxygen barrier component [28]. The result was observed and recorded in Table 3.

The TA values of uncoated mango samples in the present study recorded a lower TA value, which rapidly decreasing during storage compared to the 1.5 M ZnO-GRS sample. The observations might be due to senescence. The TA of the fruit samples was observed and recorded at the end of the storage period. The term 'senescence' refers to the inherent biological process of aging in mangoes, encompassing a range of physiological and biochemical alterations that impact attributes such as texture, flavor, appearance, and overall quality. Senescence also leads to increased sweetness and decreases the acidity of the fruit.

The 1.5 M ZnO-GRS sample recorded the highest TA level after seven days of storage at room temperature. According to Dubey et al. [28], when fruits are stored post-harvest, they continue to respire due to the prevalent acids acting as substrates for various enzymatic reactions [28]. When the respiration in fruits increases during storage, citric acid present in the fruit is broken down to sugars, decreasing the citric acid content and thus decreasing the percentage of total acid.

Table 3. The MC, TA, TSS, and pH of the samples after seven days of storage.

Sample	MC (%)	pH	TA	TSS
Control	63.53	5.576	2.2	1.6
0.5 M ZnO-GRS	55.21	5.603	1.7	1.8
1.0 M ZnO-GRS	59.09	5.704	1.8	1.6
1.5 M ZnO-GRS	69.64	5.223	2.5	1.4
2.0 M ZnO-GRS	53.76	5.629	1.7	1.8

3.4 Field Emission Scanning Electron Microscope (FESEM)

The morphology of the ZnO-GRS in the present study was investigated using FESEM. Figure 2 illustrates the images of the different concentrations of thin films at 20kX magnification, demonstrating that the ZnO NPs in all samples are spherical. Moreover, the uniformity of the dispersed ZnO-GRS in thin films on mango peels increases, corresponding to its concentration until the optimum level is reached.

According to recent research the inhomogeneity and uniformity of ZnO-GRS dispersed randomly in thin films on mango peels correlate to its concentration. In the current study, the ZnO-GRS are adequately distributed as the concentration increases to 1.5 M before clumping together. The results indicated that the optimum coating concentration is 1.5 M. Given the high surface area and surface energy of the ZnO NPs, a robust surface interaction between the ZnO nanoparticles and the matrix will result from their well-dispersed distribution [55, 56]. Moreover, the establishment of hydrogen bonds between ZnO nanoparticles (NPs) and polymers has the potential to hinder the agglomeration of nanoparticles. The occurrence of agglomeration can potentially diminish the strength of the connection within the matrix. Thus, the tensile strength of this film may be enhanced by the addition of ZnO NPs.

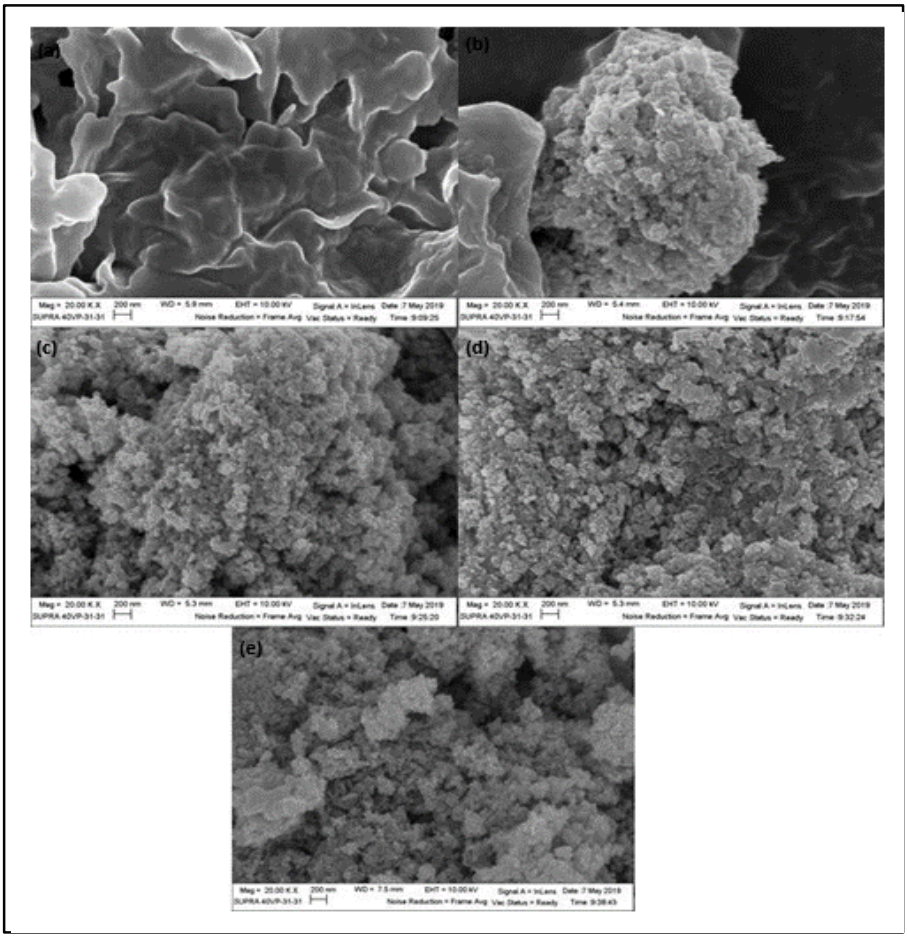

Fig. 2. The FESEM images of the (a) control, (b) 0.5, (c) 1.0, (d) 1.5, and (e) 2.0 M ZnO-GRS film coatings with mapping dot.

3.5 X-ray Diffraction (XRD)

The XRD findings justified the difference in the crystal structures of the ZnO NPs at various concentrations with the control. Figure 3 displays the amorphous peaks in the control and sharp crystalline peaks in all ZnO-GRS NPs-coated samples. The crystalline peaks reveal the cubic structure of the ZnO, which belongs to the space group Fm-3m, or the rock salt structure.

The intensity of the XRD peaks obtained in the present study is observed to be elevated with increased ZnO NPs concentration until 1.5 M before dropping. However, no phase shifts were observed when different ZnO concentrations were used. The XRD results also demonstrate that the films possessed preferential orientations along the (111), (200), and (222) planes. The (200) plane is the most prominent, recording the highest sharp peak. Consequently, the 1.5 M contains the highest amount of ZnO NPs compared to the control, 0.5, 1.0, and 2.0 M. According to Apriyanto et al. [19], a high molarity solution contains more zinc ions, which might enhance the intensity of peaks [19].

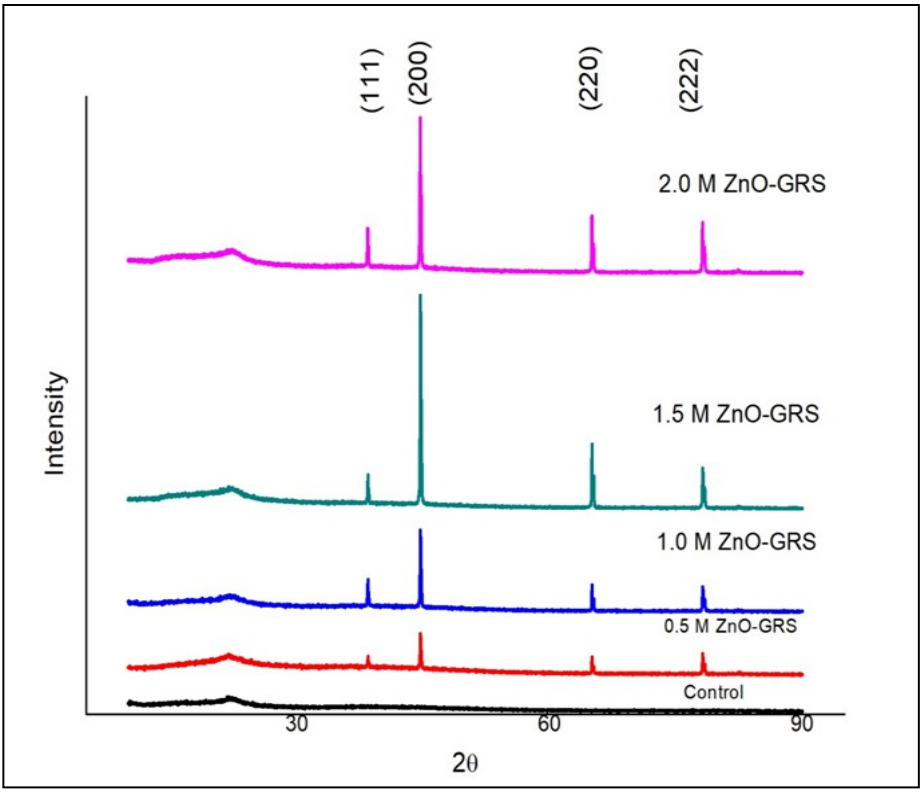

Fig. 3. The XRD peaks of the control and the samples coated with different ZnO-GRS concentrations.

3.6 Fourier-Transform Infrared (FTIR)

The FTIR spectra of the control and samples coated with different ZnO concentrations were documented between the 4000–400 cm^{-1} regions (Figure 4). The control sample recorded absorption bands at 1045.03 cm^{-1} and within 2848.03–3194.48 cm^{-1}, attributable to the C-O-H and C-H stretching of the mango peel. Meanwhile, the

ZnO NPs of the coated samples exhibited a peak at 586.97 cm^{-1} and an absorption band corresponding to starch.

The peaks observed within the 686.93–1105.73 cm^{-1} region correlated vibrations of the entire anhydroglucose ring stretching, the central part of the starch. The ring chemically reacted, improving ZnO NPs spreading on mango peel surfaces. Furthermore, the component could hold and passivate the NPs with hydroxyl groups to the positive surface charges on the ZnO via electrostatic interactions. Consequently, the glucose rings could obstruct the aggregation and growth of ZnO NPs due to steric hindrance [57].

The peaks within the 1374.74–1461.84, 1734.50–1814.11, 2848.03–29.15.44, 2847.98–2995.82, and 3651.13–3651.45 cm^{-1} ranges corresponded to C-H bonds, carbonyl group (C=O), aliphatic C-H stretching vibration of the starch, the symmetric and asymmetric stretching vibration of C-H, and the normal O-H stretching mode, respectively. The clear peaks recorded between the 3116.55–3469.03 cm^{-1} region proved the presence of O-H vibration in the ZnO and starch surfaces [27]. The ZnO detected in the O-H starch stretching band also demonstrated that the ZnO NPs adhesively bonded with the starch on the surface of the mangoes. According to Vaezi et al. [58], the observed enhancement in mechanical properties can be attributed to the interaction between ZnO NPs and biopolymers [58]. This interaction is facilitated by the ability of ZnO NPs to establish hydrogen and covalent bonds with the hydroxyl groups present in starch [29]. As a result, the molecular strength between the nanoparticles and biopolymers is reinforced.

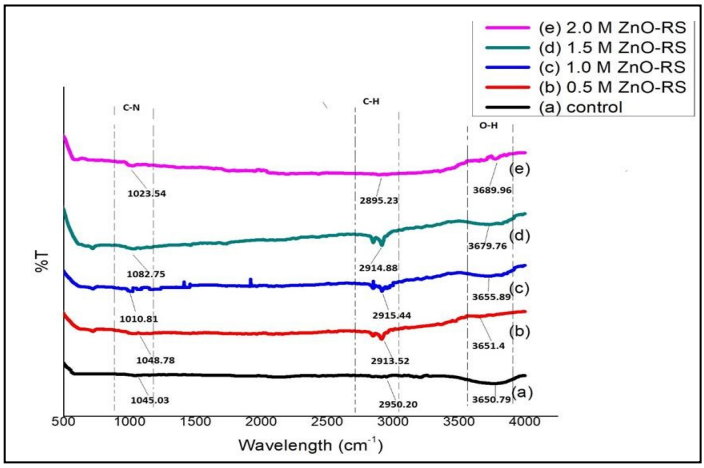

Fig. 4. The FTIR spectra of the control and the samples coated with different ZnO-GRS concentrations.

3.7 High Performance Liquid Chromatography (HPLC)

The HPLC produces rapid, accurate, and reproducible results for determining individual sugars and organic acids. Figure 5 displays the overlaid standard citric acids

chromatograms eluted from the HPLC column at 3.95 minutes. Based on the integrated peak areas, a standard calibration plot for citric acid was procured (see Figure 6).

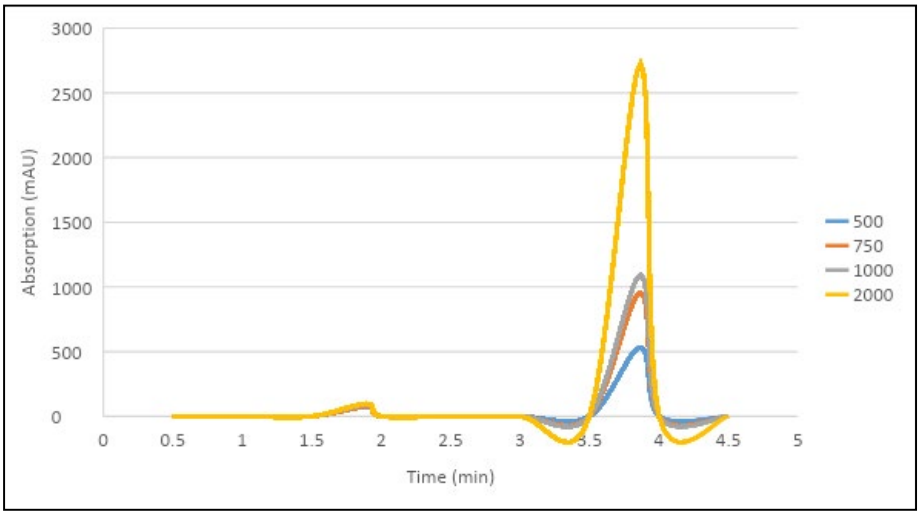

Fig. 5. The chromatograms of the 500, 750, 1000, and 2000 ppm citric acid standards.

The primary organic acid in the mango samples employed in the current study was citric acid and the values obtained via HPLC are recorded in Figure 7. Initially, the acidity of the mangoes decreased due to the high rate of citric acid loss with a slight loss of malic acid [60]. Research stated that citric acid improves the MC of the starch film [27]. A study suggested that citric acid entered the starch polymer decreasing the interactions that ultimately resulted in improving the MC [27]. A previous study reported that the major organic acid in Badami mangoes was citric acid, which diminished from 22.5 to 2.4 mEq 100 g^{-1} during ripening. In the present study, adding ZnO NPs elevated the MC of the samples [27]. It was observed in Table 4. 3 that the addition of ZnO NPs, increases the MC [27]. During the process of ripening, an improvement in the moisture content of fruit pulps contributes to the enhancement of taste and scent in fruits, as indicated by the robust positive associations observed between moisture content and taste and aroma [58].

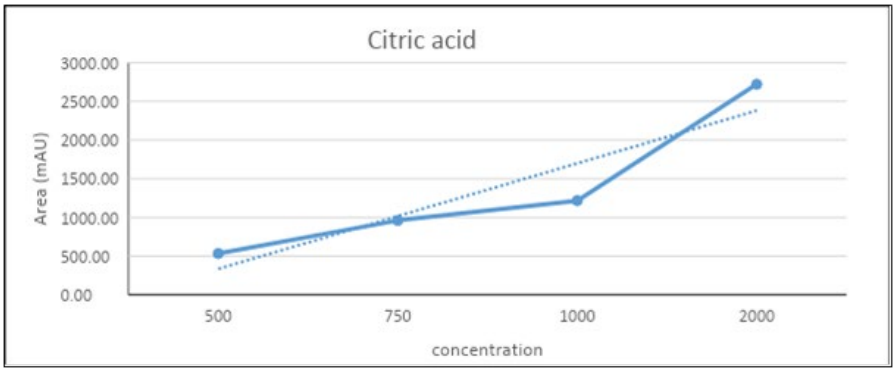

Fig. 6. The citric acid calibration plot.

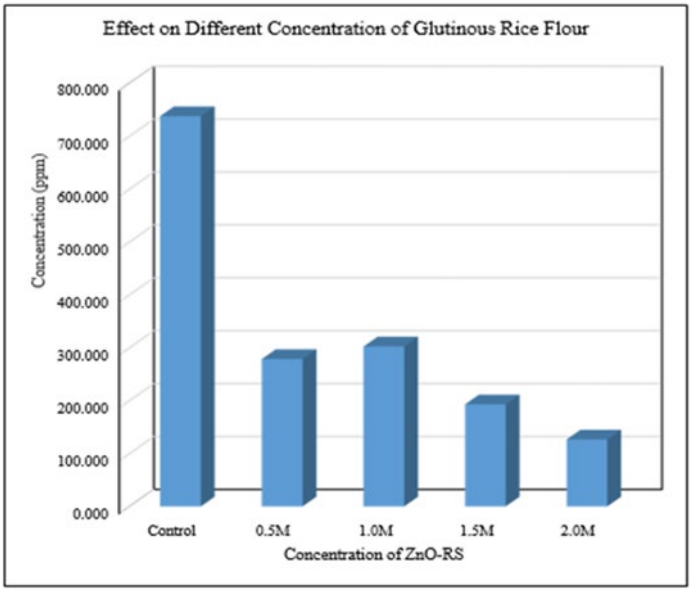

Fig. 7. Bar graph show The Concentration of Citric Acid from Control and Coated ZnO on Mango from HPLC Analysis.

4.0 Conclusion

In the current study, the ZnO-GRS coating imparted excellent effects on the shelf life and quality of mango fruits within seven days of storage. The presence of ZnO NPs was characterized via XRD, FESEM, and FTIR. The physical quality of the coated mango fruits was superior to the uncoated samples. Furthermore, anthracnose disease and microbial growth on the coated samples were reduced compared to the control. The

infection incidence and microbial growth were minimized with increasing ZnO NPs concentration.

The weight loss of the coated samples was also diminished. A higher amount of ZnO NPs minimized weight citric acid losses, thus increasing the shelf life of mango fruits during storage. The 1.5 M was the optimum concentration for ZnO-GRS coating as it recorded the highest XRD intensity, excellent ZnO NPs distribution in FESEM, favorable FTIR results, and physiochemical analysis.

Acknowledgments. The authors would like to express gratitude to the Ministry of Education Malaysia for the Geran Insentif Penyeliaan (GIP) and Fundamental Research Grants Scheme [600-IRMI 5/3/GIP (037/2018) and 600-IRMI/FRGS5/3(415/2019)] and Research Management Institute, University Teknologi Mara (UiTM), Shah Alam, Selangor, Malaysia for the financial support.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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