

## Development and Characterization of Nutmeg Shell-Based Activated Carbon for Ethylene Adsorption in Fruit Storage

Sri Ayu La Aji<sup>1</sup>, Usman Ahmad<sup>1,✉</sup>, Dyah Wulandani<sup>2</sup>

<sup>1</sup> Department of Mechanical and Biosystem Engineering, IPB University, Bogor, INDONESIA.

<sup>2</sup> Division of Biosystem Engineering, Department of Mechanical and Biosystem Engineering, IPB University, Bogor, INDONESIA.

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Corresponding Author:

✉ [usmanahmad@apps.ipb.ac.id](mailto:usmanahmad@apps.ipb.ac.id)  
(Usman Ahmad)

### ABSTRACT

*Nutmeg shells are categorized as hardwood containing carbon such as cellulose and lignin, making them ideal for use as a material for producing activated charcoal. Activated charcoal can be used as an additive to absorb ethylene, O<sub>2</sub>, CO<sub>2</sub>, and H<sub>2</sub>O to slow down fruit ripening. This study was conducted to produce and characterize ethylene absorbers made primarily from Fakfak nutmeg shells and to determine the effectiveness of ethylene absorbers in delaying the ripening of climacteric fruits. Ethylene adsorbents were produced using a pyrolysis method followed by chemical activation. Characterization of surface area and functional groups was performed through SEM and BET tests, as well as FT-IR tests. To ensure the effectiveness of the absorption capacity, the chemical-physical properties were characterized in accordance with Standard of Indonesia and gas chromatography. The results of the activated charcoal test showed a change in the surface area from 298.211 m<sup>2</sup>/g to 335.198 (BET). FT-IR test results showed the formation of functional groups, namely -OH, C=C, CO<sub>2</sub>, C-H, and C-O groups. GC test results showed 90.5% ethylene absorption. The application of nutmeg shell adsorbent on bananas using sealed LDPE plastic packaging showed that nutmeg shell adsorbent was able to maintain banana quality up to 15 days, although there was no significant difference between treatments ( $p > 0.05$ ).*

## 1. INTRODUCTION

Nutmeg is known as a spice plant with high economic value. Fakfak nutmeg belongs to the *Myristicaceae* family, has a large tree size, big and broad leaves, as well as large, elongated fruit. According to [Musaad et al. \(2017\)](#), Fakfak nutmeg has unique characteristics in terms of its physical, morphological, and genetic attributes, compared to other types of nutmeg found in Papua, especially Banda nutmeg. Fakfak nutmeg fruit contains 90.20% fruit flesh, 7.46% seeds, 1.23% mace, and 1.12% shell. Nutmeg shell is categorized as hardwood containing high levels of carbon, such as cellulose and lignin. The shell also contains chemical compounds such as crude fiber 53.67%, hemicellulose 46.82%, cellulose 21.34%, lignin 12.93%, ash 6.16%, carbonyl 0.38%, and phenol 0.11%. This is what makes nutmeg shells very suitable for use as raw material in the production of activated charcoal.

Activated charcoal is derived from raw materials that are high in carbon, cellulose, hemicellulose, and lignin, which are activated through a combustion process to create pores with a large surface area, giving it properties as a selective adsorbent depending on the size or volume of the pores and the surface area. Research conducted by [Hitijahubessy \(2019\)](#) found that nutmeg shell waste can be used as activated charcoal that functions as an adsorbent. The quality of the activated charcoal produced met the SNI -1995 Quality Standard, namely moisture content of 0.70%, volatile matter content of 3.88%, total ash content of 8.73%, fixed carbon content of 87.39%, and an iodine adsorption capacity of 325.07 mg/g. The use of activated charcoal as an adsorbent to inhibit the ripening process of

fruit has been carried out by [Markiah & Rahmi \(2020\)](#) using palm kernel shells as adsorbents, which can extend the shelf life of kepok bananas up to 12 days. Another study was conducted by [Rizaldi & Hestianingsing \(2023\)](#) using bidara wood as an adsorbent. Tomatoes stored for 10 days using bidara wood adsorbent showed an effect on weight loss and total dissolved solids. Based on the chemical composition produced from previous studies, nutmeg shells are also rich in carbon and lignocellulose compounds, making them suitable as raw materials for activated charcoal. Activated charcoal produced from biomass with these characteristics is known to have a pore structure and surface area that supports the adsorption process, making it potentially applicable as an adsorbent in fruit ripening control. Nutmeg shell has more porosity than other palm kernel shell and wood in general so that it is expected to have more ability to function as gas adsorbent and even more by applying carbon activation to it.

Fruit ripening is an important process that determines the quality and shelf life of fresh fruit products after harvest. During the ripening process, fruit undergoes changes such as becoming sweeter in taste, the flesh becoming softer, developing a distinct aroma, and experiencing changes in skin color. Climacteric fruits are types of fruit that experience a significant increase in ripening after harvest due to the rate of respiration and the presence of the hormone ethylene. During ripening in climacteric fruits, ethylene regulates color changes and the reduction of chlorophyll levels, an increase in carotenoids or anthocyanins, sugars, and the biosynthesis of volatile organic compounds ([Iqbal \*et al.\*, 2017](#)). Postharvest bananas are classified as climacteric fruits, which continue to ripen after being picked as a result of increased respiration and ethylene production. The higher the rate of respiration and ethylene production, the faster the fruit will spoil. In addition, bananas have a relatively short shelf life, averaging between 1 and 10 days, making them prone to serious postharvest losses ([Zulkifli \*et al.\*, 2016](#)). To control the ripening process in climacteric fruits, many methods are used in postharvest handling, such as controlled atmosphere storage, chitosan coating, and the use of  $\text{KMnO}_4$  ([Kafiya & Wicaksono. 2023](#); [Aprilia \*et al.\*, 2023](#)). The ripening process can also be slowed by adding materials that can absorb ethylene,  $\text{O}_2$ ,  $\text{CO}_2$ , and  $\text{H}_2\text{O}$ , such as activated charcoal from nutmeg shells. However, the performance gap between controlled adsorption systems and real fruit storage conditions remains underexplored. The objective of this study was to develop and characterize ethylene absorbers made primarily from Fakfak nutmeg shells and to determine the effectiveness of ethylene absorbers in delaying the ripening of climacteric fruits.

## 2. MATERIALS AND METHODS

The research was carried out at the Laboratory of Agricultural Product Processing Technology, Faculty of Agricultural Technology, Bogor Agricultural Institute; the Forest Product Chemistry Laboratory, Faculty of Forestry, Bogor Agricultural Institute; the Laboratory of the Central Agency for Environmental and Forestry Standardization, Bogor; the GR-DNA IP2SIP Muara Laboratory - BRMP Rice, Ministry of Agriculture; the BRMP Postharvest Laboratory, Ministry of Agriculture, from March to July 2025. The equipment used in this study included a pyrolysis furnace, Gas Chromatography, Zeiss EVO 50 Model for Scanning Electron Microscopy (SEM) testing, Micromeritics, Gemini analyzer for the Brunauer Emmet Teller (BET) test, Fourier Transform Infrared Spectroscopy (FTIR), refractometer, chromameter, and digital scales. The materials used were activated charcoal from nutmeg shells, bananas as the fruit sample,  $\text{CaCl}_2$  2% (Merck),  $\text{KMnO}_4$  2% (Merck), distilled water, tissue, filter paper, starch, iodine, ascorbic acid, LDPE plastic with a thickness of 0.045 mm, and tyvek paper with a thickness of 68 gsm.

### 2.1. Preparation of Ethylene Adsorbent from Nutmeg Shells

Clean nutmeg shells were pyrolyzed at a temperature of 700 °C for one hour, followed by chemical activation using a 2%  $\text{CaCl}_2$  activator solution, in which the material was soaked for 24 h. It was then rinsed repeatedly with distilled water until it reached a neutral pH, and subsequently filtered using filter paper. The resulting residue was dried in an oven at 120 °C for 2 h. The char obtained from the oven was then stored in a desiccator until stabilized, after which it was referred to as activated charcoal. The produced activated charcoal was then characterized using the Scanning Electron Microscopy (SEM) method at 1000x magnification to observe the surface area of the activated charcoal before and after activation. This was followed by specific surface area, pore volume, and pore diameter characterization using the Brunauer-Emmet-Teller (BET) method through nitrogen ( $\text{N}_2$ ) adsorption at a temperature of -196 °C, and the Fourier Transform Infrared Spectroscopy (FT-IR) method to observe the functional groups formed after

activation. To ensure the quality, adsorption effectiveness, and conformity to national standards, the chemical-physical properties were characterized, including moisture content, ash content, volatile matter content, fixed carbon content, and iodine adsorption capacity. The characterization results (benchmark) were compared with the technical activated charcoal values according to SNI 06–3730-1995 (BSN, 1995). Subsequently, adsorption capacity tests for specific gases were conducted using gas chromatography.

## 2.2. The Effectiveness Test of Ethylene Absorption in Banana Ripening.

The tests for controlling fruit ripening include evaluations of various important factors such as weight loss, firmness, total soluble solids, and color. These assessments aim to measure the effectiveness of the control method in maintaining the quality and nutritional value of the fruit during storage, ensuring the fruit remains fresh and fit for consumption, as well as determining the effectiveness of the adsorbent used. Bananas were stored in tightly sealed LDPE plastic packaging (without perforation) to create a closed storage system. Before observation, bananas of approximately 1 kg were first packaged using LDPE plastic, then the adsorbent wrapped in tyvek paper at amounts of 3.5 g, 7 g, and 10 g, as well as a control, are placed and stored at room temperature ( $27\pm 2$  °C) for 15 days. During storage, bananas are packed in LDPE plastic bags placed inside woven baskets. The purpose is to ensure a uniform volume inside each package, as there is currently no information regarding the appropriate package size for storing bananas weighing approximately 1 kg. The storage treatment is carried out to observe how long the adsorbent influences the extension of the banana's shelf life. The experiment is repeated 3 times, resulting in a total of 12 experimental units. Observations were carried out on days 0, 2, 6, 10, and 15.

## 3. RESULTS AND DISCUSSION

Activated nutmeg shell charcoal is produced physically through a low-oxygen pyrolysis process, which involves the dehydration and devolatilization of the biomass material with a yield of about 30.92% to 32.01%. Research conducted by Maryati & Patimang (2024) produced yields of activated charcoal from Papua nutmeg seeds ranging from  $39.19\pm 0.23$  to  $42.61\pm 0.11\%$  at a temperature of 450 °C for 35 minutes. These differences in yield are likely influenced by the duration and temperature of the burning process used. This is in accordance with the statement by Okezua *et al.* (2025) that the parameters affecting activated charcoal production are carbonation temperature and time.

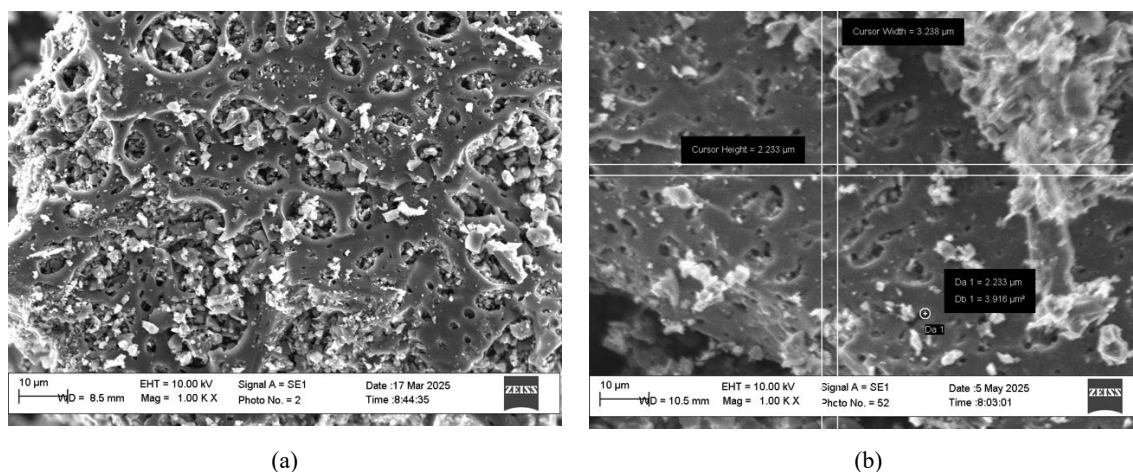


Figure 1. SEM test results (a) before chemical activation (b) after chemical activation with 1000x magnification

### 3.1. Characteristics of Nutmeg Shell Activated Charcoal

SEM test results before chemical activation show that most of the pores in the activated charcoal are still covered by impurities; however, after activation, the surface of the activated charcoal appears cleaner. In Figure 1a, the surface of activated charcoal appears uneven, rough, and hollow, with pores still covered by residual carbonation process

residues, whereas after chemical activation (Figure 1b), the pore surface appears cleaner and more open. This shows that the chemical activation process is capable of opening pores and surface structures. The cleaner-looking pore surface is due to the  $\text{CaCl}_2$  chemical compound used in the chemical activation process, which serves to dissolve impurities in the charcoal, such as inorganic minerals and tar, thereby making the pores of the activated charcoal cleaner.

Table 1. BET test results

Tested parameters	Before chemical activation	After chemical activation
Single point surface area at $p/p_0 = 0.20000$	298.211 $\text{m}^2/\text{g}$	335.198 $\text{m}^2/\text{g}$
Total pore volume at $p/p_0 = 0.99000$	0.141 $\text{cm}^3/\text{g}$	0.164 $\text{cm}^3/\text{g}$
Average pore diameter (4V/A)	2.176 nm	2.219 nm

BET test result for the activated charcoal before and after chemical activation show differences in surface area, from 298.211  $\text{m}^2/\text{g}$  to 335.198  $\text{m}^2/\text{g}$ , the pore volume of the activated charcoal from 0.141  $\text{cm}^3/\text{g}$  to 0.164  $\text{cm}^3/\text{g}$ , and the pore size from 2.176 nm to 2.219 nm (Table 1). The increase in BET values indicates that chemical activation is effective in enlarging the surface area and pore volume, making the resulting activated charcoal more reactive and efficient in absorbing molecules. According to [Jamilatun et al. \(2015\)](#), the longer the soaking time, the larger the surface area. The greater the surface area, the higher the iodine number or the better the quality of the activated charcoal.

The results of FT-IR testing (Figure 2) show the formation of several functional groups. This indicates that during the carbonation process at a heating temperature of 700 °C, the chemical structure is decomposed and several functional groups are formed. In the wavenumber region of 3400  $\text{cm}^{-1}$ , stretching is observed which is identified as vibrations from hydroxyl groups (-OH). The presence of OH groups formed is likely due to the decomposition of chemical compounds and residual moisture that was not completely broken down during the carbonation process. Absorption in the region with a wavenumber of 2360.01  $\text{cm}^{-1}$  is suspected to be caused by vibrations of the carbon dioxide ( $\text{CO}_2$ ) functional group. Some studies revealed that decreased absorption intensity affects the formation of aromatic compounds from carbon atoms in activated charcoal ([Menendez et al., 1999](#); [Erçin & Yürüm, 2003](#); [Kimura et al., 2004](#)). Furthermore, absorption in the region with a wavenumber of 1630  $\text{cm}^{-1}$  is suspected to be caused by vibrations of the aromatic functional group (C=C). According to [Park et al. \(2013\)](#), the carbonation and activation processes of activated charcoal will increase aromatic compounds, which are the constituents of the hexagonal structure of charcoal and activated charcoal. The higher the activation temperature during carbonation, the more robust the formation of aromatic groups becomes. The formed aromatic compounds originate from the lignin present in nutmeg shells. Then, absorption in the region with a wavenumber of 1400-1000  $\text{cm}^{-1}$  is suspected to be caused by vibrations of alkane (C-H) and alkoxy (C-O) groups. The presence of these functional groups on the surface of the charcoal makes it slightly polar. In addition, the greater the content of carbon elements in the activated charcoal, the stronger its ability to absorb fluids and bind substances that come into contact with the carbon atoms.

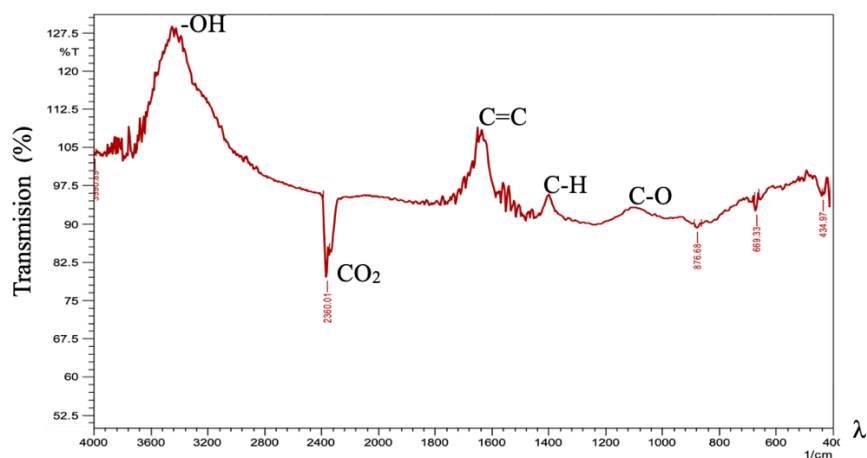


Figure 2. FT-IR test results

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The increase in surface area and pore openness after chemical activation shows the potential for an increase in the number of adsorption sites and ease of ethylene molecule diffusion into the pore structure of activated charcoal. The presence of aromatic carbon groups on the surface of activated charcoal is thought to contribute to physical interactions with ethylene. However, given that ethylene is a nonpolar and relatively inert molecule, the effect of functional groups on ethylene adsorption is likely to be limited, so that surface area and pore characteristics are expected to be more dominant factors.

### 3.2. Effectiveness of Activated Carbon Adsorption

The effectiveness of activated carbon adsorption testing based on SNI 06-3730-1995 is used to assess the general quality and physical properties of the activated carbon produced, while gas chromatography (GC) testing is used to assess the actual ability of activated carbon to absorb specific gases such as ethylene. The test results using GC with an ethylene injection of 1000 ppm for 8 h showed that the ethylene concentration decreased by 90.15%. These results indicate that activated charcoal combined with 2%  $\text{KMnO}_4$  effectively reduces ethylene concentration due to a combination of physical adsorption (pores and surface area) and chemical oxidation, which converts ethylene into inactive products. Statistical analysis, however, showed that the effect is not significant. This suggests that laboratory-scale adsorption performance does not directly translate into real storage systems due to humidity-induced pore saturation and limited gas exchange. According to Keller *et al.* (2013),  $\text{KMnO}_4$  is a good oxidizing and adsorbing compound. The combination of physical adsorption from activated charcoal (pores and surface area) with chemical oxidation from  $\text{KMnO}_4$  causes ethylene to become an inactive product. This is also in line with the statement by Aprilliani *et al.* (2018) that activated charcoal combined with  $\text{KMnO}_4$  is capable of removing ethylene through oxidation, where  $\text{KMnO}_4$  adsorbed on the surface of activated charcoal reacts with ethylene, causing a significant decrease in ethylene concentration during the experiment.

Table 2. shows a comparison of the adsorption results of nutmeg shell activated charcoal with SNI 1995 activated charcoal. In general, activated charcoal from nutmeg shells meets four of the five SNI parameters, namely moisture content, volatile substances, ash, and fixed carbon. However, the iodine adsorption capacity ( $420.52\text{ mg/g}$ ) is still below the minimum standard ( $750\text{ mg/g}$ ). This indicates that the number of micropores in activated charcoal is still not optimal, despite an increase in the surface area of activated charcoal.

Table 2. Comparison of the results of characterization of nutmeg shell ethylene absorbers with SNI 1995

Parameters	Nutmeg Shell Adsorbent (%)	SNI 06-3730-1995
Moisture content	0.72	Max 15 (%)
Volatile matter content	6.00	Max 25 (%)
Ash content	2.56	Max 10 (%)
Carbon content	91.44	Min 65 (%)
Iodine absorption capacity	420.52	Min 750 mg/g

The moisture content was calculated and found to be 0.72% below the maximum limit of SNI-1995. Low moisture content causes the pores in activated charcoal to open up, thereby increasing the surface area of activated charcoal (Yulianti *et al.*, 2010). Low water content increases the adsorption capacity of activated charcoal. Conversely, higher water content can reduce the adsorption quality of activated charcoal. This is in line with the statement by Jamilatun *et al.* (2015) that high water content reduces the adsorption capacity of activated charcoal towards gases and gas liquids.

The volatile matter content was calculated and found to be 6.00%, below the maximum limit of SNI-1995, which is 25%. Low levels can be influenced by high temperatures and long activation times, which cause carbon erosion during washing, as well as by the temperature during pyrolysis. This is in line with Hartanto & Ratnawati (2010) that high volatile matter levels are caused by low temperatures and short burning times. The ash content value plays an important role in determining the quality of activated charcoal and can affect its adsorption capacity. The ash content in nutmeg shell activated charcoal is 2.56%, which is below the maximum limit of SNI-1995 and still meets the standard. According to Okezua *et al.* (2025), a decrease in ash content indicates an increase in surface area.

The calculation results obtained a fixed carbon value of 91.44%, which is above the minimum standard limit of SNI-1995, which is 65%, and has met the quality standard. The high fixed carbon value is influenced by the low ash content, high volatile matter, and particle size. The higher the fixed carbon, the better the quality of the activated charcoal. This is in line with research conducted by Erawati & Fernando (2018), which states that the higher the fixed carbon value, the better the quality of the activated charcoal.

Factors affecting iodine adsorption include the chemical activator, the duration of activation, the temperature, and the duration of baking after activation (Jamilatun *et al.* 2015). The calculation results obtained an iodine adsorption value of 420.52 mg/g, which is below the minimum SNI-1995 standard of 750 mg/g. The low iodine adsorption value may be due to the low concentration of activator used. The low iodine number suggests limited microporous structure, which is critical for adsorption of small molecules such as ethylene. This is in line with the research by Radika & Astuti (2020) that the lower the concentration of activator used, the fewer the number of pores, which will affect the surface area of activated charcoal in the adsorption of iodine solution, and vice versa. The duration of immersion also affects the ability of activated charcoal to absorb iodine. This is in line with the statement by Jamilatun *et al.* (2015), that the longer the immersion time, the greater the surface area, resulting in higher iodine numbers.

### Ethylene Adsorption to Control Fruit Ripening

During the ripening delay process, changes occur in the banana fingers, where on the second day white hyphae begin to appear on the banana fingers. The appearance of white hyphae indicates the emergence of fungi. The presence of fungi can be influenced by the temperature during the storage process, which causes significant evaporation inside the packaging. According to Kader (2013), temperature affects the growth of pathogens during storage. The relationship between packaging and the type of adsorbent treatment on weight loss, hardness, TDS, and color related to L and Hue values is not significantly different. Each treatment has the same changes in weight loss, hardness, TDS, and color.

Weight loss of bananas for each adsorbent treatment in sealed LDPE packaging without holes was observed for 15 days based on a 5% ANOVA test, which showed a significant effect on weight loss ( $p < 0.05$ ), but storage duration had no significant effect on changes in weight loss (Figure 3). The results indicate that adsorbents used with tightly sealed LDPE packaging without holes can suppress changes in weight loss in bananas. This is in line with the research by Thompson (2001) and Zerga Heterat & Tsegaye (2020), which states that the physiological weight loss in fruits packaged with polyethylene plastic is lower than that in other packaging materials. Weight loss is also influenced by enzyme changes due to high air temperature during storage, which causes turgidity in bananas, which causes turgidity in bananas (Nyalala & Windwright, 1998).

A decrease in hardness indicates the onset of ripening in bananas. The results of the 5% ANOVA test showed no significant effect between each treatment on changes in banana hardness ( $p > 0.05$ ), but storage duration had a significant effect on hardness (Figure 4). The use of tightly sealed LDPE packaging without holes was able to extend the shelf life of the fruit to 15 days. Observations also found that some of the bananas were rotten on the last day of observation. The rot could have been caused by fungi present at the base of the bananas. The emergence of fungi can be influenced by the amount of water vapor adhering to the packaging due to the increased rate of CO<sub>2</sub> production

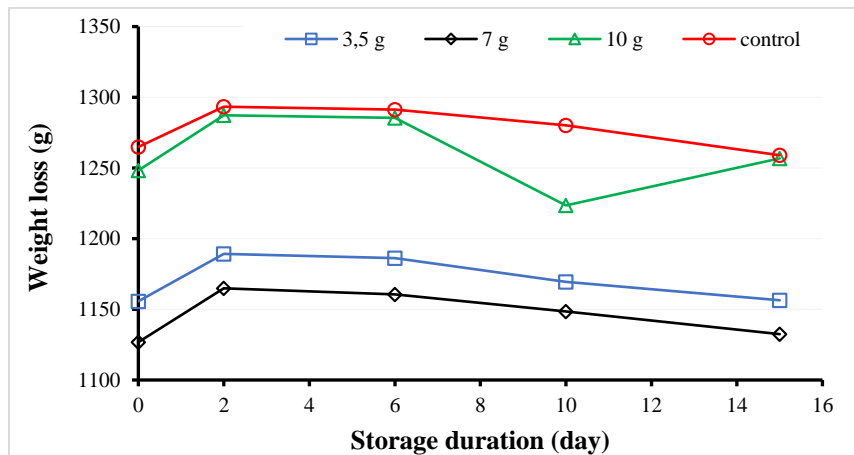


Figure 3. Line diagram showing the effect of adsorbents on banana fruit weight loss

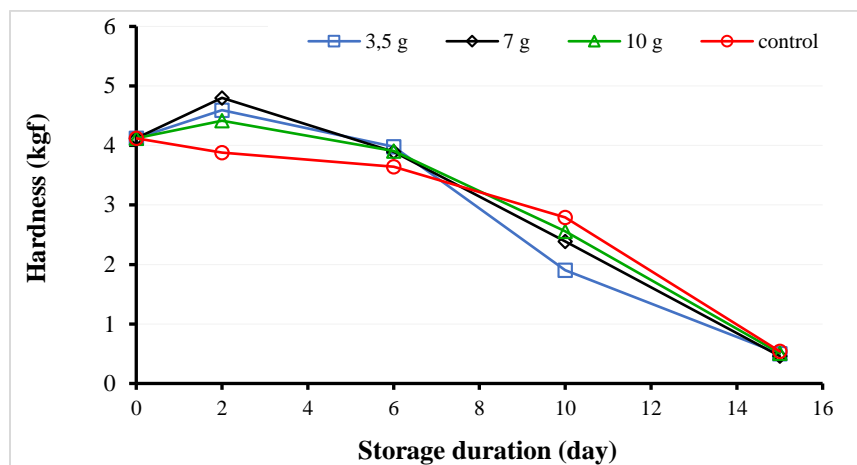


Figure 4. Line diagram showing the effect of adsorbents on banana fruit hardness

during storage. This is in line with the statement by [Widodo \*et al.\* \(2011\)](#), which states that comb-shaped samples have the potential to retain water vapor and heat from respiration, which ultimately encourages the growth of fungi and accelerates fruit deterioration. The decrease in weight loss was followed by a decrease in the hardness of the banana skin. The decrease in hardness was characterized by the texture of the banana becoming soft and slightly watery. According to [Barret \*et al.\* \(2002\)](#) the water content in food will affect the proportion and structure of solids, resulting in a soft texture.

The increase in TDS value during delayed ripening is caused by the breakdown of carbohydrates and pectin, the hydrolysis of proteins, and changes in the composition of glycoside compounds during respiration ([Athmaselvi \*et al.\* \(2013\)](#)). The TDS value plays a role in giving bananas their sweet taste. The sweetness resulting from high TDS values can be influenced by harvest age. The older the harvest age, the higher the TDS value ([Agustiningrum \*et al.\*, \(2018\)](#)).

Figure 5 shows an increase in TDS content in bananas during storage in all treatments, and the results of the 5% ANOVA test for each treatment showed no significant effect on banana TDS values ( $p > 0.05$ ), while storage duration had a significant effect on TDS values. The maximum TDS value (21.64 0Brix) was observed in bananas with a 7g adsorbent treatment on the last day of observation. The increase in TDS value was caused by amylase and phosphorylase enzymes in the metabolic process that occurs in the fruit, where starch is converted into simple sugars ([Arifiya, \(2017\)](#)). According to [Aprilia \*et al.\* \(2023\)](#), higher TPT values indicate that the adsorbent does not halt the ripening process but merely slows down the ripening time.

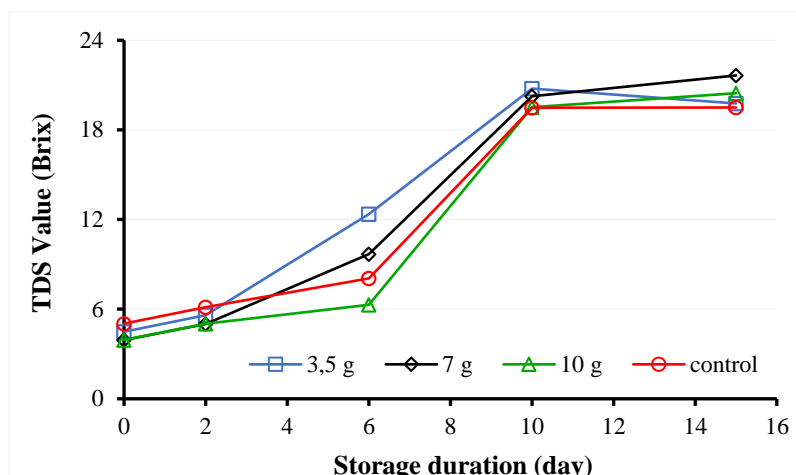


Figure 5. Line diagram showing the effect of adsorbents on the TDS value of bananas

Color changes in fruit are a basic criterion for determining fruit ripeness. The  $L^*$  value indicates brightness, and the Hue value indicates the hue angle (base color) of the fruit skin during storage. The results of the analysis of variance (ANOVA) showed that for each adsorbent treatment, there was no significant effect on changes in the Hue value ( $p > 0.05$ ). Meanwhile, storage duration tended to influence changes in Hue values, although not yet significant at the 5% level. This indicates that adsorbents packaged in tightly sealed LDPE bags without holes significantly inhibit changes in  $L^*$  and Hue values. In addition, the harvest age of bananas, the position of each bunch on the cluster, and the different weights of the fruit will affect the respiration rate and metabolism of each bunch, which can influence color changes in bananas (Zhu *et al.*, 2010). Based on Figure 6 (a), the  $L^*$  color (brightness) has a value of around 56-58. This indicates that the banana color is becoming brighter green. The higher the L value, the brighter the banana skin color, and the lower the L value, the darker the banana skin color. Meanwhile, for the Hue value (hue angle), Figure 6 (b) has a value of around 105, indicating a yellowish-green color.

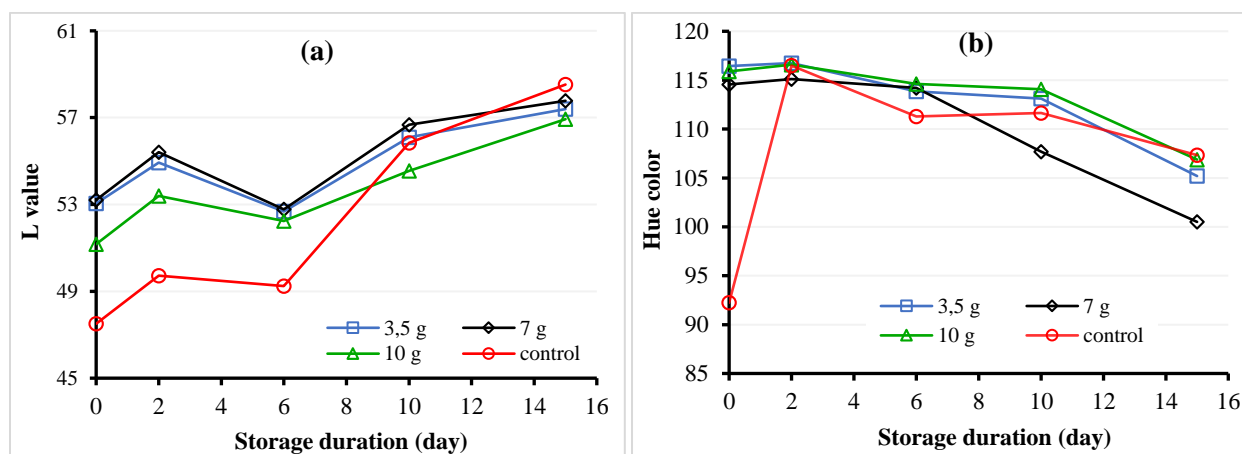


Figure 6. Linear diagram of the effect of adsorbents on (a) L value (b) Hue value of bananas

The absence of differences between the treatment and control groups is thought to be due to the use of tightly sealed LDPE plastic packaging, which limited air exchange and resulted in relatively uniform gas and humidity conditions for all samples. The humidity inside the packaging was influenced by temperature and relative humidity (RH). During the 15 days of storage, the temperature ranged from 25–30 °C and the RH ranged from 66–83%. According to Luampon & Charmongkolpradit (2019), RH affects the amount of water vapor that can be absorbed by

the sample to reach a state of humidity equilibrium, while temperature affects the rate and mechanism of water vapor transfer through plastic. These conditions cause water vapor to accumulate inside the packaging, so that the hygroscopic activated carbon tends to become saturated as it absorbs more water. The fact that the adsorbent becomes saturated with water rather than ethylene is likely due to the fact that, during storage, water vapor first appears on the surface of the packaging as a result of respiration, while the climacteric peak has not yet occurred. By the 7th day, when the climacteric process occurs and ethylene is released, the adsorbent is presumed to have absorbed more water, thereby reducing its ability to adsorb ethylene. In addition, the relatively low concentration of the activator is presumed to have been insufficient to oxidize ethylene effectively, resulting in no significant difference between the treatment and control groups. Consider of putting moisture absorber might be necessary in the research to keep the ability of ethylene adsorber in the packaging.

#### 4. CONCLUSIONS

The activated carbon produced showed an increase in surface area from 298.211 m<sup>2</sup>/g to 335.198 m<sup>2</sup>/g, in pore volume from 0.141 cm<sup>3</sup>/g to 0.164 cm<sup>3</sup>/g, and in pore diameter from 2.176 nm to 2.219 nm, indicating its potential as an adsorbent. GC test results showed that the nutmeg shell adsorbent was capable of reducing ethylene concentration by up to 90.15%. However, the use of a relatively low concentration of activator and the use of tightly sealed LDPE plastic packaging for bananas resulted in suboptimal performance of the activated carbon in absorbing ethylene. These packaging conditions led to the accumulation of water vapor, causing the activated carbon to become saturated due to the absorption of water, which was more dominant than that of ethylene gas. The combination of these factors resulted in no significant difference in ethylene uptake compared to the control.

#### AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
SALA	✓	✓			✓	✓	✓	✓	✓	✓				✓
UA	✓	✓		✓					✓	✓		✓		
DW	✓	✓		✓					✓	✓		✓		

C: Conceptualization	Fo: Formal Analysis	O: Writing - Original Draft	Fu: Funding Acquisition
M: Methodology	I: Investigation	E: Writing - Review & Editing	P: Project Administration
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

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