Time-Temperature Tolerance of Harvested Green Bananas Exposed to High Temperatures

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Time-Temperature Tolerance of Harvested Green Bananas Exposed to High Temperatures

(高温に曝された収穫後緑熟バナナの時間温度耐性)

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1.1 Background

1.1.1 The global banana supply chain

Bananas are a popular crop in world agricultural production and trade. According to the FAO (2020a), banana is consumed at a rate of around 13 kg person^{-1} year^{-1} in Japan, India, China, Russia, the USA, and Europe. Furthermore, banana production and trade volume by producing countries has increased rapidly over recent decades; moreover, the consumption of banana is predicted to continue to increase as the world population grows. More than 1,000 banana varieties currently exist and all of these are grown as edible produce. The most commercialized banana variety is "Cavendish" (*Musa acuminata*, AAA group, Cavendish subgroup) which is estimated to account for around 40–50% of global banana production. Moreover, all exported banana varieties are "Cavendish" because it is better suited to international trade than other varieties because of its high production yields.

Banana fruit holds a crucial role, contributing significantly to food security and serving as a source of export revenue in certain countries (Siddiq et al., 2020). Throughout history, bananas have been a key driver of economic stability in rural farming communities, providing employment for local farmers and curbing migration to urban areas in search of alternative livelihoods (Al-Busaidi, 2013). The economic importance of bananas is underscored by their role as a cash crop, often serving as the primary source of income for rural populations and playing a vital role in poverty alleviation. Due to its affordability and ease of production, bananas are particularly significant for low-income societies and families (Hailu et al., 2013). Consequently, bananas hold essential ecological and socioeconomic significance (Al-Dairi et al., 2023).

The supply chain for bananas involves various operations, including production, transportation, distribution, handling, storage, and packaging (Al-Dairi et al., 2022). Bananas, being climacteric and perishable fruits, are prone to relatively high postharvest losses, especially during transportation, handling, and storage (Wasala et al., 2014). The entire supply chain faces challenges such as climate change, disease outbreaks, labor conditions, and trade tariffs, all of which can significantly impact the availability and losses of bananas. Postharvest losses result from multiple factors, including insufficient human knowledge and inadequate infrastructure. It has been reported banana losses are around 10%–80% in Ecuador (Vásquez-Castillo et al., 2019) and 3%–30% in the Philippines (Aquino-Nuevo and Apaga, 2010).

The banana supply chain includes farming, harvesting, packing, shipping, distribution, and retail. Figure 1 illustrates the different of postharvest handling of bananas for domestic and global market. The global banana supply chain is a complex that involves multiple stages and actors as shown in Figure 2. Bananas are grown on large-scale monoculture plantations, typically in tropical countries such as Ecuador, the Philippines, China, Brazil, India, and Indonesia, with the fruit primarily grown on large plantations spanning several hundred hectares (Voora et al., 2020). Notably, the Philippines and Ecuador have more than 160,000 hectares of banana plantations (FAO, 2020b).

(a)

(b)

Figure 1: Bananas postharvest handling for domestic market (a) and global market (b) (some pictures were adopted from the internet and personal documentation at Great Giant Food Company, Lampung Province, Indonesia).

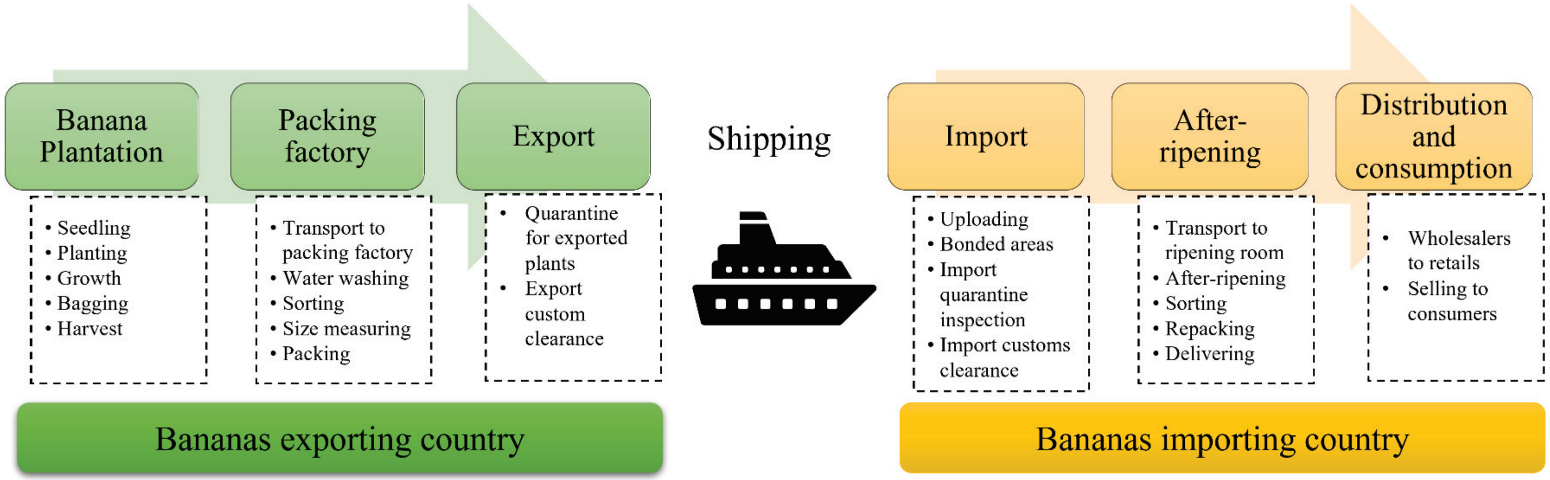

Figure 2: The illustration of banana supply chain for global market (Source: https://www.nipponexpress.com/press/report/06-Nov-20.html).

The intricate journey of the banana supply chain initiates with the cultivation and planting of bananas in the exporting country. The flowers of banana trees bloom, transitioning from square-shaped to rounded fruits, a process which takes 70 to 100 days. Harvesting starts when the banana fruits exhibit a light green color. Notably, bananas are exceptional in that they can be harvested year-round, owing to their distribution in tropical and subtropical regions. Following harvest, the bananas undergo thorough washing, sorting, weighing, and packing at a local processing facility. Each cardboard box bears an identity code, encompassing details such as the farm of origin, packing facility, and date and time of packing, ensuring traceability. After export inspections, including phytosanitary checks, the bananas embark on a maritime journey, enduring weeks at sea to reach their destination.

Maintaining freshness during this voyage is achieved through the utilization of temperature-controlled reefer containers. Modern advancements include the integration of Remote Container Management (RCM) technology by some shipping companies. This allows remote monitoring of parameters like power supply, temperature, humidity, and ventilation settings, ensuring the safe transportation of bananas.

Upon arrival in the importing country, bananas do not directly enter the market. Instead, packed banana pallets undergo ripening in dedicated rooms. Import regulations often prohibit the import of yellow-colored bananas, necessitating ripening upon arrival. Green, hard bananas are placed in ripening rooms, categorized by shipping date, and subjected to a 4 to 7-day ripening process in a controlled environment with adjusted temperature, ethylene gas, and hydrocarbons. Maintaining a constant temperature is crucial, as deviations below 13 °C or above 18 °C can compromise the appearance of bananas. Once ripened to the desired state, bananas are transferred to cooling rooms. Now ready for consumption, the bananas are shipped to wholesalers and retailers before reaching the ultimate consumers.

FAO (2020a) reported significant milestone in global banana exports, recording approximately 21 million tons in 2019, reflecting a 10% increase from the preceding year. Ecuador and the Philippines emerged as the leading banana exporters. In Ecuador, the total banana production escalated from 6.18 to 6.48 million tons, with 97% allocated for export, a high export rate was maintained as of 2017–2019. Meanwhile, the Philippines, with a slightly smaller total banana production hovering around 6 million tons over the same period, witnessed a substantial surge in export rates, rising drastically from 45% (2.70 million tons) to 73% (4.33 million tons). Notably, only 15% of the world's total banana production is presently traded globally, with the majority used for local consumption. The reported global import volume of bananas in 2019 amounted to approximately 19 million tons. Prominent importers such as the European Union and the USA accounted for 1% and 3% of these imports, respectively.

1.1.2 Physiological characteristics of banana after harvest

Respiration is a crucial factor in preserving the quality of fruits and vegetables, especially in bananas. Since banana is a climacteric fruit, its respiration rate increases during ripening in contrast to the respiration rate of non-climacteric fruits (Sugianti, et al., 2022). Hailu et al., (2013) stated that respiration involves the breakdown of carbohydrates, proteins, and fats into simple final products with ATP released as energy. Sugar and organic acids are two major respiratory substrates found in all fruits; they are insulated within the vacuoles. The composition of sugar and organic acids contributes to the formation of flavor in fruit and affects its taste. Commonly O_2 is used, and CO_2 is produced in a respiration process; this leads to senescence depending on the rate of respiration. The more the respiration rate increases, the faster the fruit deteriorates in quality (Irtwange SV, 2012).

Under practical conditions, banana is harvested at the green maturity stage when the respiration rate is low and ethylene production is almost undetectable. Hailu et al (2013) termed this stage “green life” or the “pre-climacteric period.” After harvesting, the respiration rate of green Cavendish bananas is about 20 mg CO_2 kg^{-1} h^{-1} when stored for a couple of days at 20 °C. At the climacteric peak of four days of storage, the respiration rate significantly increases up to 250 mg CO_2 kg^{-1} h^{-1} after which it declines gradually in the post-climacteric stage (Xu et al., 2019). As well as the transpiration process, the respiration process reduces the total weight of the banana. Consequently, in marketing systems, the quantity of bananas produced is reduced by the respiration process, which can result in reduced commodity value. Therefore, to preserve the quality of bananas, respiration should be always considered when applying postharvest technology.

1.1.3 Ethylene synthesis during ripening

The biosynthetic pathway of ethylene is associated with ripening and senescence (Figure 3) (Alexander L and Grierson D, 2002). Fundamental ethylene biosynthesis usually includes three major steps. First, the amino acid methionine, a precursor of ethylene in higher plants, is catalyzed by S-adenosyl methionine (SAM) synthase at the expense of one molecule of ATP per molecule. Second, SAM is converted to 1-aminocyclopropane 1-carboxylic acid (ACC) by ACC synthase (ACS). Because of oxygen, ACC is converted to ethylene by ACC oxidase (ACO) (Inaba et al., 2007; Mbeguie-A-Mbeguie D et al., 2008). Next, receptors (ETRs, ERSs, EIN4) perceive ethylene, which are negative regulators located at the endoplasmic reticulum. In the absence of ethylene, Constitutive Triple Response (CTR1) is activated through the inactivation of Ethylene Insensitive 2 (EIN2). Therefore, ethylene response is suppressed by CTR1. The primary transcription factor involves Ethylene Insensitive 3 (EIN3)/Ethylene Insensitive 3 like 1 (EIL1) to activate a transcriptional cascade. As a result, the Ethylene Response Factor (ERF) regulates genes underlying the ripening process of bananas (Maduwanthi SDT and Marapana RAUJ, 2019).

Some genes related to ethylene biosynthesis and related pathways in bananas, including *ACS*, *ACO*, ethylene receptor, a CTR1 orthologue, and ethylene insensitive 3-like genes, have previously been investigated (Maduwanthi SDT and Marapana RAUJ, 2019; Choudhury et al., 2012). The promoters of major ripening genes in banana fruits are *MaACS1* and *MaACO1*. *MaACS1* was reported to be phosphorylated by a Ser/Thr protein kinase during fruit ripening, which increases the stability of the protein and induces ethylene production (Choudhury et al., 2012; Terra et al., 1983). Importantly, Xiao et al. (2013) reported the role of the ethylene response factor (ERF) and transcription factor (TF) in the transcriptional regulation of ethylene synthesis by regulating *MaACS1* and *MaACO1*. It was proved that *MaERF9* activated the promoter of *MaACS1*, while *MaERF11* repressed the promoters of *MaACS1* and *MaACO1*. As a result, MaERFs play a significant role in banana fruit ripening via transcriptional regulation of or interaction with ethylene biosynthesis genes.

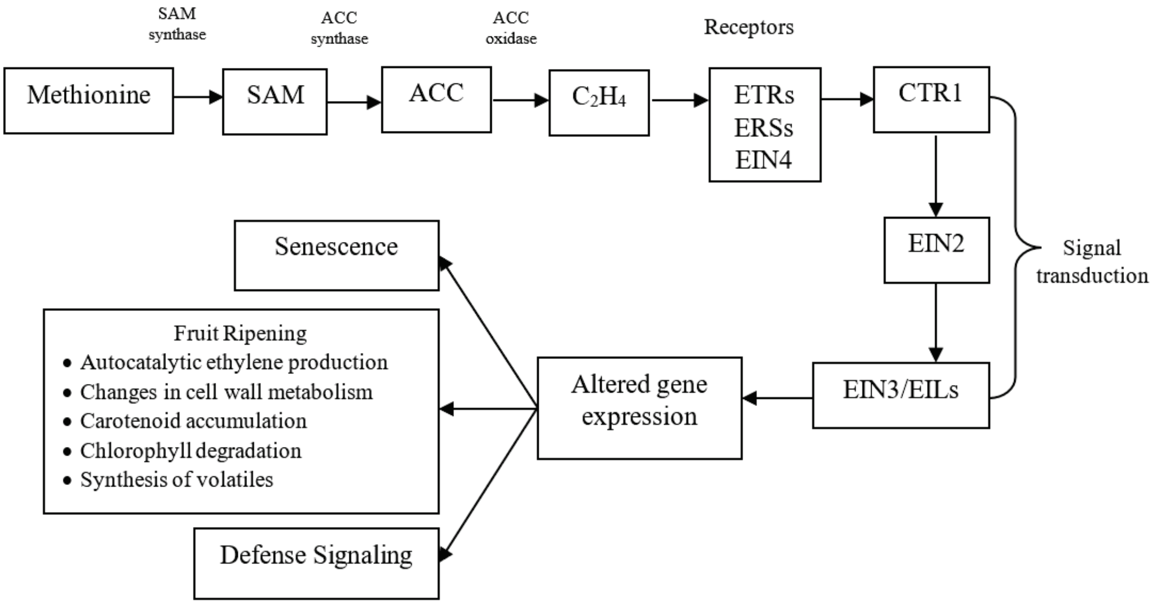

Figure 3: Ethylene biosynthesis pathway and signal transduction (Alexander L and Grierson D, 2002)

The ethylene production rate increases according to the stage of maturity, mechanical injuries, disease, and increasing temperature up to 30 °C. In contrast, low temperatures, reduced O_2, and increased CO_2 levels around the commodity suppress ethylene production (Hubbard et al., 1990). Both endogenous ethylene and exogenous ethylene can alter the quality changes to the color, texture, sweetness, aroma, volatile production, and nutritional value of bananas.

1.1.4 Biochemical and physical changes of banana during ripening

After harvesting, the banana continues to ripen, and the biochemical characteristics of the fruit drastically change. These biochemical changes are summarized in Table 1. The most changed biochemical compound during ripening is starch which is abundant in bananas. At the unripe stage, the starch level in bananas is high; levels decrease to a deficiency during ripening due to the conversion of starch into soluble sugars. Simultaneously, the levels of soluble sugars, such as sucrose, glucose, and fructose, which are the main detectable compounds in ripened bananas, increase. Initially, sucrose is the predominant soluble sugar at the onset of ripening. Subsequently, fructose followed by glucose becomes the main soluble sugars (Adão RC and Glória MBA, 2005; Phillips et al., 2021).

Fatty acids can be categorized as saturated fatty acids (SFAs), monounsaturated fatty acids, and polyunsaturated fatty acids. The major fatty acids in bananas are palmitic (16:0), stearic (18:0), oleic (18:1), linoleic (18:2), and linolenic (18:1) acids (Nadeeshani et al., 2021; Morais., 2017; Longvah et al., 2017). Phenolics are important secondary metabolites in banana peel and are contained at a higher level compared with those found in other fruits (Maduwanthi SDT and Marapana RAUJ, 2021). The phenolic compounds in banana peel are categorized into four subgroups, hydroxycinnamic acids, flavonols, flavan-3-ols, and catecholamines (Vu et al., 2018). Bioactive amines are also contained in bananas and their levels decline during ripening. Dopamine and noradrenaline are susceptible to enzymatic browning; these substances are responsible for such reactions in bananas (Adão RC and Glória MBA, 2005). The peel color of banana turns from green to yellow because of the degradation of chlorophylls (Maduwanthi SDT and Marapana RAUJ, 2021; Wall, 2006). Overall, these changes contribute to the appearance and quality of ripened bananas.

Table 1 Estimated biochemical compounds in bananas.

Compound (units)	**Banana varieties / Origins**	**Contents**		**References**
		Green stage	**Yellow stage**	
Carbohydrate in pulp				
Starch (g/100 g)	Prata Banana / Brazil	15.7	3.4	(Adão RC and Glória MBA, 2005)
	Cavendish	13	2	(Phillips et al., 2021)
Fructose (g/100 g)	Prata Banana / Brazil	0.52	6.27	(Adão RC and Glória MBA, 2005)
	Cavendish	1.5	7	(Phillips et al., 2021)
Glucose (g/100 g)	Prata Banana / Brazil	0.35	4.63	(Adão RC and Glória MBA, 2005)
	Cavendish	1.5	7	(Phillips et al., 2021)
Sucrose (g/100 g)	Prata Banana / Brazil	0.39	3.4	Adão RC and Glória MBA (2005)
	Cavendish	1	3	(Phillips et al., 2021)
Fatty acid in pulp				
Palmitic acid (16:0) (mg/100 g)	Kolikutttu / Sri Lanka	-	90.88	(Nadeeshani et al., 2021)
	Musa sp / Brazil	-	242.6	(Morais et al., 2017)
	Montham / India	-	103	(Longvah et al., 2017)
Stearic acid (18:0) (mg/100 g)	Kolikutttu / Sri Lanka	-	6.84	(Nadeeshani et al., 2021)
	Musa sp / Brazil	-	16.9	(Morais et al., 2017)
	Montham / India	-	6.8	(Longvah et al., 2017)
Oleic acid (18:1) (mg/100 g)	Kolikutttu / Sri Lanka	-	13.15	(Nadeeshani et al., 2021)
	Musa sp / Brazil	-	26.5	(Morais et al., 2017)
	Montham / India	-	8.73	(Longvah et al., 2017)
Linoleic acid (18:2) (mg/100 g)	Kolikutttu / Sri Lanka	-	51.07	(Nadeeshani et al., 2021)
	Musa sp / Brazil	-	145.2	(Morais et al., 2017)

Compound (units)	Banana varieties / Origins	Contents		References
		Green stage	Yellow stage	
α-linolenic acids (18:3) (mg/100 g)	Kolikutttu / Sri Lanka	-	39.71	(Nadeeshani et al., 2021)
	Musa sp / Brazil	-	186.4	(Morais et al., 2017)
Vitamins and Minerals in pulp				
Vitamin A (µg/100 g)	Kolikutttu / Sri Lanka	-	14.37	(Nadeeshani et al., 2021)
Vitamin D_2 (µg/100 g)	Kolikutttu / Sri Lanka	-	0.4	
Vitamin E (µg/100 g)	Kolikutttu / Sri Lanka	-	81.44	
Vitamin K_1 (µg/100 g)	Kolikutttu / Sri Lanka	-	1.81	
Vitamin B_1 (µg/100 g)	Kolikutttu / Sri Lanka	-	51.18	
Vitamin B_2 (µg/100 g)	Kolikutttu / Sri Lanka	-	83.9	
Vitamin C (mg/100 g)	Kolikutttu / Sri Lanka	-	14.1	
Pottasium (K) (mg/100 g)	Kolikutttu / Sri Lanka	-	554	
Calcium (Ca) (mg/100 g)	Kolikutttu / Sri Lanka	-	45.5	
Magnesium (Mg) (mg/100 g)	Kolikutttu / Sri Lanka	-	38	
Phenolic compounds in pulp				
Gallic acid equivalent (mg/g)	Musa AAB group / Sri Lanka	-	39.69	(Maduwanthi SDT and Marapana RAUJ, 2021)
The total amount of amines in pulp (mg/100g)	Prata Banana / Brazil	3.52	3.12	(Adão RC and Glória MBA, 2005)

Compound (units)	Banana varieties / Origins	Contents		References
		Green stage	Yellow stage	
Chl degradation in peel				
Chl a (mg/cm^2)	Musa AAB group / Sri Lanka	7.74	0.6	(Maduwanthi SDT and Marapana RAUJ, 2021)
Chl b (mg/cm^2)	Musa AAB group / Sri Lanka	4.9	1.1	
β-carotene (µg/100 g)	Dwarf Brazilian / Hawaii	-	73	(Wall, M.M., 2006)
	Williams / Hawaii	-	42.8	
α-carotene (µg/100 g)	Dwarf Brazilian / Hawaii	-	92.6	
	Williams / Hawaii	-	60	

1.1.5 Postharvest technologies, issues, and challenges for bananas postharvest management

1.1.5.1 Artificial ripening technology

For practical reasons, bananas are harvested for the commercial market at the mature green stage or pre-climacteric stage. Naturally ripened bananas are not appropriate for commercial purposes because fruits become over-ripened during distribution due to the nature of climacteric fruit; this results in a significant economic loss for traders. Therefore, artificial ripening of bananas is a postharvest technology that is considered important for minimizing losses during transportation, achieving timely distribution, and fulfilling consumer expectations (Maduwanthi SDT and Marapana RAUJ, 2019).

The design of ripening room conditions should be optimized to tightly control the banana ripening process. The ripening room should be equipped with refrigeration, heating, and air circulation systems. The room should also be sealable to prevent the loss of ripening-inducing agents such as ethylene gas (C_2H_4). During the ripening process, a large quantity of heat is released from the banana; therefore, sufficient refrigeration capacity should be installed to control temperature. In subtropical areas, a heating system is needed to maintain room temperature during the cold season. In addition, the ripening room must have an adequate air circulation system; good circulation and a proper airflow pattern produce uniform banana ripening (Sugianti, et al., 2022).

As an example, photos of the banana ripening room in operation are shown in Figures 4 (a) and (b). The maximum processing capacity of the ripening room shown in the photo is 40 tons per chamber. The banana boxes are stacked with each hand-held hole and ventilation apertures exactly aligned, and the wall side of the stack is placed along a sheet to prevent air leakage. The airflow direction of this system is illustrated in Figure 4 (c). The air with C_2H_4 is suctioned by fans on the ceiling and blows out from the top of both side walls, then passes into each banana box through the hand-hold hole. The static pressure generated by the air circulation fans provides uniform airflow through the ventilation apertures of the box. In a typical case, the temperature of the chamber is set at 20 °C on the first day of processing and reduced to 15 °C over four or five days. The temperature is controlled based on the experience of the operator depending on the desired ripeness. The degree of ripening is supplementarily monitored by the concentration of carbon dioxide in the chamber, which is generated by bananas' respiration.

Ethylene (C_2H_4) gas is commonly used for artificial ripening of bananas. The artificial ripening technique is conducted in a ripening room equipped with ventilation and exhaust systems under an optimum temperature, relative humidity, and with C_2H_4. Banana is fumigated with C_2H_4 gas at a concentration of 10–150 ppm for 2–3 days (Saltveit, 1999). After fumigation, the fruit is brought to the optimum ripening temperature. Low level C_2H_4 concentrations, such as 0.1 ppm, can accelerate the ripening of bananas. Another study reported that exposure to C_2H_4 at 100 ppm for 12 h induces endogenous ethylene immediately and raises CO_2 production as in the climacteric respiratory process (Hubbard et al., 1990).

(a) (b) (c)

Figure 4: The exterior and interior of the banana ripening room (a) ripening chambers, (b) ripening room condition (Pictures were taken by authors at Unifrutti Japan Corporation, Tokai, Ota-ku, Tokyo on 30 January 2020), and (c) an illustration of air flow direction in the ripening room (Source: Sugianti, et al., 2022).