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CHILI (*CAPSICUM SP.*) SHELF LIFE AND GENETIC VARIABILITY ANALYSES IN FRUIT CELLS' STRUCTURE

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SUMMARY

In postharvest storage, longer shelf life is one of the crucial characteristics for preserving the freshness of chili (*Capsicum* sp.). The following study aimed to identify the chili genotypes with prolonged shelf life and examine the storage effects on the fruit cells' structure. The genetic material comprised 25 chili genotypes, including six genotypes of the species *C. frutescens*, three from *C. chinense*, and 16 from *C. annuum*, incurred growing in a randomized complete block design with three replications. The collection of chili fruit samples with 80% maturity came from all the genotypes before placing them in plastic trays and storing them at room temperature (25 °C–27 °C, 60%–70% RH). In chili fruits, the morphological and cytological variation observations used an Aquilos-2 cryo-focused ion beam at 65× to 2500× magnification until 50% weight loss. Shelf life traits emerged closely associated with the genetic makeup of the chili genotypes. The chili genotypes revealed significant variations for shelf life. Three chili genotypes, namely, Katokon, SSP, and Selektta were notable with sustainable longer shelf life for more than 16 days, as indicated by slower fruit weight loss and less cell deterioration. Fruit water loss (FWL) proved to be the key trait in determining the shelf life of the chili genotype fruits.

Keywords: Chili (*Capsicum* sp.), cytological analysis, fruit weight loss, genotypes, postharvest, shelf life

Key findings: Chili (*Capsicum* sp.) fruit shelf life is crucial in postharvest handling. Fruit water loss revealed the variations in chili fruit cells and their shelf life. Breeding programs need to find selection parameters for shelf life that are quick, simple, and economical.

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INTRODUCTION

The chili (*Capsicum* sp.) breeding program aimed to combine all essential characteristics into one cultivar, which may have higher productivity and shelf life, better resistance to diseases and pests, and more bioactive chemicals (Karim *et al.*, 2021). The variety development process begins with selecting the promising genetic material, which determines the best crossing parental genotypes. The selection happened using direct and indirect methods. Indirect selection of chili parental genotypes relied on the morphological traits previously observed to provide significant insights into effective pre-breeding, management, and utilization strategies for crop improvement (Zhigila *et al.*, 2014). Identifying new sources of genetic diversity will obtain the desired genotypes after being properly described for easy use (Karim *et al.*, 2021). Commonly grown chili cultivars belonged to the species *Capsicum annuum*, *Capsicum frutescens*, *Capsicum baccatum*, and *Capsicum chinense* (Prasad *et al.*, 2022). Some chili species are climacteric intermediates, displaying a hybrid ripening behavior between the climacteric and non-climacteric categories (Hao *et al.*, 2018).

Capsicum sp. is a horticultural commodity with significant price fluctuations in Indonesia. Factors affecting these price fluctuations include supply and demand imbalances (Anwarudin *et al.*, 2015). Farid and Subekti (2012) reported that chili prices are volatile due to seasonal variations, rainfall patterns, production costs, and distribution channels. Fresh chili peppers are perishable, lose weight, and deteriorate at room temperature. Following harvest, the chili loses water, wilts, and changes color (Samira *et al.*, 2013; Huo *et al.*, 2021). The chili fruit quality declines after harvesting as it contains more moisture, which causes it to respire faster during storage (Samira *et al.*, 2013).

The most common symptoms of chili fruit deterioration are wrinkling, softening, and rotten fruits. Muflikh and Kiloes (2024)

mentioned that the decreased fruit freshness affects its price and consumer preferences. The chili with higher water content promotes respiration during storage, and respiration also cannot be stopped. This process generates heat and promotes the microclimate (Banya *et al.*, 2020). Microorganisms can proliferate in the conditions of elevated temperature and humidity during storage, leading to significant economic losses in fruit quality and quantity (Ali *et al.*, 2016).

Water loss in chili fruits seems to incur genetic influences. Cultivars observed with the specific morphologies and processes regulate water losses. Water loss varies among the species and cultivars because of the variations in fruit characteristics. These characteristics include the ratio of fruit surface area to volume, the fruit surface morphology (stomata and lenticels), and the cuticle thickness and composition (Lufu *et al.*, 2020). Chilies with low rates of water loss have the highest lipid content, except for linoleic acid (Maalekuu *et al.*, 2006). The simple straight-chain aliphatic cuticle constituents form impermeable cuticular barriers versus more complex isoprenoid-based compounds (Parsons *et al.*, 2012). Cuticle damage is thought to alter cell signaling, affecting epidermal differentiation (Lara *et al.*, 2019).

The different mechanisms to maintain chili fruits' freshness have been widely reported before. Temperature treatment (Hameed *et al.*, 2015; Fikiru *et al.*, 2024), use of packaging materials (Chitravathi *et al.*, 2020), and the addition of chemicals (Panigrahi *et al.*, 2017) can also extend the shelf life of chili fruits. However, all these methods require additional costs. The development of new chili cultivars with longer shelf life is one of the primary solutions. The promising research aimed to determine the level of shelf life of chili genotypes and assess the fruit cells' damage during storage. The results of this study will provide fast and easy recommendations for the selection of traits supporting the shelf life of chili genotypes.

MATERIALS AND METHODS

Genetic material

The chili (*Capsicum* sp.) genotypes' planting at the Experimental Station of Leuwikopo, Bogor Agricultural University, Indonesia, with geographical coordinates of -6.563800° South latitude and 106.726083° East longitude and an elevation of 250 masl. The genetic material comprised 25 chili genotypes, including six genotypes from the species *C. frutescens*, three from *C. chinense*, and 16 genotypes from *C. annuum*. The experiment layout was in a randomized complete block design with three replications. In total, there were 75 experimental units, and each unit contained 20 plants. Observations occurred on 10 fruits per experimental unit as postharvest samples.

Storage treatment

The harvested chili fruits at 80% maturity sustained washing with water before being arranged in plastic trays. The fruit samples' storage had a room temperature of 25 °C–27 °C with 60%–70% RH. Sample selection followed the chili fruit maturity index (Hendrawan *et al.*, 2021), where harvested samples at stadia index 8 are predominantly red, with a slight green or overall bright red, bright, and shiny. Fruit water loss (FWL) observation occurred daily, with chili fruit samples weighed with two decimal accuracy. The observations ended when the fruit water loss reached 50%. The weight loss determination employed the following formula (Haile, 2018):

$$\text{Weight Loss (\%)} = \frac{\text{Weight of initial} - \text{Weight of final}}{\text{Weight of initial}} \times 100$$

Genotypes screening

The observations on the FWL served as the foundation for the clustering process. The grouping procedure took place through the implementation of the data classification system, where the number of classes formed aligns with the Sturges formula as follows (Sugiyono, 2021):

$$K = 1 + 3.3 \log n$$

Where K = the number of classes and n = the number of data.

Scanning electron microscope

The chili fruit samples earlier stored for 14 days, as well as the control, were specimens used for the study. The fruits' cross-sectioning used a scalpel, with the samples placed on the SEM stub and vacuumed. Then, samples' observation under an Aquilos 2 Cryo-Focused Ion Beam (Thermo Fisher Scientific, USA) electron microscope had magnifications ranging from 65× to 2500×. The captured visible images documentation used the xT Microscope Control (Thermo Fisher Scientific, USA).

Data analysis

All collected data underwent the analysis of variance (ANOVA) test. Differences among the various treatments, as identified, used the Tukey test at $P \leq 0.05$. The analysis employed the Minitab version 16 software.

RESULTS AND DISCUSSION

Chili genotypes' screening

The diversity of the early storage chili (*Capsicum* sp.) fruit phenotypes of various genotypes, along with each genotype's response during storage, appears in Table 1. The chili genotypes varied for fruit length, and the genotype Caman showed the longest fruits and fruit peduncles. Genotype Katokon had the highest fruit weight and diameter. Fruit length and exocarp thickness had no considerable effect on water loss in chili fruits during storage (Do-Rêgo *et al.*, 2024). The chili fruits have cavities limiting their water-holding capacity. Water loss from the fruit leads to diminished firmness and quality, and eventually, reduced shelf life and market value. The deterioration of chili fruits exhibited the loss of water, the onset of shriveling, discoloration, and the necrotic degeneration of the pericarp (Samira *et al.*, 2013).

Table 1. Diversity in fresh chili fruit traits based on descriptors (IPGRI, 1995).

Genotypes	Fruit shape	Fruit color		Fruit length (cm)	Peduncle length (cm)	Fruit diameter (mm)
		Young	Ripe			
<i>Capsicum frutescens</i>						
Feira	Elongated	Greenish Yellow	Red	5.06 ^{def}	3.33 ^{def}	8.30 ^{gh}
Bonita	Elongated	Greenish Yellow	Red	3.80 ^{defg}	2.80 ^{defgh}	11.00 ^{cdefgh}
Pulai Pila	Elongated	Greenish Yellow	Red	5.92 ^d	3.12 ^{defg}	9.54 ^{fgh}
RJHLxHiyung-7-25H	Elongated	Green	Red	5.41 ^{de}	3.58 ^{cdef}	9.35 ^{fgh}
RJHLxHiyung-7-28H	Elongated	Green	Red	5.01 ^{def}	3.44 ^{cdef}	10.56 ^{efgh}
ORI 212	Elongated	Greenish Yellow	Red	4.24 ^{defg}	2.73 ^{defgh}	11.04 ^{cdefgh}
<i>Capsicum chinense</i>						
Peach Chupetinho	Almost round	Green	Peach	1.79 ^g	1.76 ^h	14.45 ^b
Red Chupetinho	Almost round	Green	Red	2.52 ^{fg}	1.74 ^h	12.76 ^{bcde}
Katokon	Blocky	Green	Red	4.03 ^{defg}	2.91 ^{defgh}	25.06 ^a
<i>Capsicum annuum</i>						
Seroja	Elongated	Purple	Red	2.76 ^{efg}	2.69 ^{efgh}	11.16 ^{cdefgh}
Viola	Elongated	Purple	Red	3.62 ^{defg}	2.00 ^{gh}	10.81 ^{defgh}
Arisa	Elongated	Green	Red	11.10 ^{bc}	3.55 ^{cdef}	11.26 ^{cdefg}
Adelina	Elongated	Purple	Red	9.73 ^c	2.72 ^{defgh}	8.57 ^{fgh}
Fish Pepper	Triangular	Green	Red	3.44 ^{defg}	2.00 ^{gh}	13.70 ^{bcd}
Anies	Elongated	Green	Red	12.23 ^{bc}	3.66 ^{cdef}	12.67 ^{bcde}
F5 136074xImperial-3-1-1	Elongated	Greenish Yellow	Red	10.64 ^c	2.58 ^{fgh}	10.21 ^{efgh}
F5 F6074xImperial-7-7-5	Elongated	Greenish Yellow	Red	11.62 ^{bc}	4.59 ^{abc}	10.05 ^{efgh}
F5 AniesxBaja-3-8-8	Elongated	Green	Red	12.23 ^{bc}	3.66 ^{cdef}	12.67 ^{bcde}
F5 ImperialxF6136074-2-1-1	Elongated	Greenish Yellow	Red	10.74 ^c	3.88 ^{bcde}	11.46 ^{bcdef}
SSP	Elongated	Green	Red	11.20 ^{bc}	3.30 ^{def}	8.93 ^{fgh}
Pesona	Elongated	Green	Red	12.24 ^{bc}	3.77 ^{cdef}	8.23 ^h
Seloka	Elongated	Green	Red	10.17 ^c	3.93 ^{bcd}	13.85 ^{bc}
Selekta	Elongated	Green	Red	10.77 ^c	3.81 ^{bcde}	13.79 ^{bcd}
Caman	Elongated	Green	Red	17.78 ^a	5.31 ^a	9.26 ^{fgh}
Neno	Elongated	Green	Red	13.63 ^b	5.00 ^{ab}	9.12 ^{fgh}
Tukey Test p ≤ 0.05				2.75	1.22	2.99
Coefficient of variation (%)				24.99	11.39	7.97

Numbers followed by the same letter are not significantly different in the Tukey test at 0.05 level.

Wide variations among the chili genotypes for quantitative traits and fruit length, diameter, weight, and fruit yield showed the highest heritability (Verma *et al.*, 2024). Chili fruit color can served as an indicator of ripeness. Typically, unripe fruits are green, whereas ripe fruits range in color from yellow to red. Each flower contains a single ovary, comprising multiple seeds (Zhigila *et al.*, 2014). The fruit's pulp was the ovary wall, called the pericarp, which also varies in thickness. The fruit interior had carpels divided with separating tissue. Numerous seeds are evident on the placenta. The fruit's physical characteristics include round, square, and rectangular shapes, with specifications such as thick to elongated and

tapered pericarp walls and thinner walls (O'Donoghue *et al.*, 2018).

The water loss s in the chili fruits at post-harvest was characterized by a daily reduction in fruit weight. day (Table 2). This phenomenon is attributed to genotype-specific responses to storage conditions. However, the rate of water loss differed among genotypes, with some reaching up to 50% loss. Additionally, differences in the rate of water loss were also prominent within the genotypes of the same species. The genotype significantly impact on shelf life duration, while shelf life characteristics were further influenced by the interaction of genotype, environment, and management practices (Schober *et al.*, 2022).

Table 2. Fruit weight per day (g) of the chili genotypes of three different species during storage at room temperature. Observations started when the fruit weight was 50% of the initial weight (numbers marked in bold).

Genotypes	Shelf life (days)																		Fruit Weight 50% (g)	
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17		18
<i>Capsicum frutescens</i>																				
Feira	1.87	1.73	1.63	1.54	1.44	1.32	1.19	1.04	0.89	-	-	-	-	-	-	-	-	-	-	0.94
Bonita	1.97	1.79	1.70	1.59	1.48	1.34	1.23	1.14	1.03	0.96	0.81	0.71	-	-	-	-	-	-	-	0.99
Pulai Pila	2.54	2.28	2.16	1.98	1.81	1.66	1.50	1.40	1.35	1.30	1.18	1.17	-	-	-	-	-	-	-	1.27
RJHLxHiyung-7-25H	2.02	1.81	1.71	1.60	1.50	1.39	1.27	1.19	1.09	1.02	0.92	-	-	-	-	-	-	-	-	1.01
RJHLxHiyung-7-28H	2.07	1.88	1.75	1.63	1.53	1.42	1.30	1.20	1.10	1.02	1.08	-	-	-	-	-	-	-	-	1.03
ORI 212	2.56	2.36	2.20	1.98	1.82	1.63	1.45	1.34	1.24	1.10	1.08	0.96	-	-	-	-	-	-	-	1.28
<i>Capsicum chinense</i>																				
Peach Chupetinho	1.83	1.71	1.63	1.54	1.46	1.38	1.28	1.20	1.13	1.08	1.00	0.94	0.88	-	-	-	-	-	-	0.91
Red Chupetinho	1.62	1.53	1.47	1.40	1.34	1.28	1.22	1.13	1.10	1.06	1.00	0.89	0.84	0.79	0.73	0.68	0.62	-	-	0.81
Katokon	7.20	7.03	6.87	6.74	6.61	6.49	6.36	6.27	6.11	6.02	5.87	5.65	5.48	5.24	4.91	4.64	4.34	4.06	3.73	3.60
<i>Capsicum annum</i>																				
Seroja	1.70	1.57	1.49	1.39	1.31	1.22	1.09	1.07	0.99	0.93	0.85	0.74	-	-	-	-	-	-	-	0.85
Viola	2.09	1.98	1.87	1.77	1.69	1.59	1.47	1.40	1.30	1.20	1.12	1.02	0.95	-	-	-	-	-	-	1.04
Arisa	6.40	5.97	5.65	5.38	5.05	4.73	4.43	4.15	3.80	3.46	3.22	3.24	3.16	2.92	-	-	-	-	-	3.20
Adelina	4.11	3.90	3.75	3.62	3.45	3.26	3.08	2.95	2.84	2.72	2.57	2.44	2.36	2.28	2.21	2.13	-	-	-	2.06
Fish Pepper	3.19	2.98	2.87	2.72	2.60	2.48	2.32	2.19	2.08	1.97	1.82	1.75	1.62	1.57	1.48	-	-	-	-	1.59
Anies	9.31	8.74	8.24	7.79	7.41	6.84	6.42	6.09	5.80	5.42	5.31	5.01	4.66	4.09	3.92	3.59	3.34	-	-	4.65
F5 136074xImperial-3-1-1	5.69	5.39	5.10	4.85	4.57	4.29	4.10	3.91	3.65	3.31	3.09	2.91	2.71	2.52	-	-	-	-	-	2.85
F5 F6074xImperial-7-7-5	6.25	5.78	5.35	5.03	4.66	4.29	4.09	3.85	3.31	2.87	2.51	2.42	-	-	-	-	-	-	-	3.13
F5 AniesxBaja-3-8-8	9.31	8.74	8.24	7.79	7.41	6.84	6.42	6.09	5.80	5.42	5.31	5.01	4.66	4.09	3.92	-	-	-	-	4.65
F5 ImperialxF6136074-2-1-1	7.25	6.82	6.50	6.21	5.90	5.62	5.34	5.13	4.81	4.52	4.19	3.82	3.56	3.42	2.40	2.22	2.18	-	-	3.62
SSP	4.76	4.23	4.15	3.97	3.83	3.67	3.53	3.37	3.24	3.12	3.05	2.90	2.79	2.70	2.57	2.42	2.31	2.22	-	2.38
Pesona	5.11	4.68	4.28	3.90	3.48	3.11	2.73	2.49	2.24	2.08	1.74	1.62	-	-	-	-	-	-	-	2.56
Seloka	8.54	8.11	7.75	7.46	7.18	6.93	6.63	6.34	6.05	5.75	5.42	5.17	4.90	4.60	4.28	3.91	3.76	-	-	4.27
Selekta	9.14	8.72	8.39	8.12	7.86	7.61	7.36	7.07	6.83	6.56	6.30	6.02	5.78	5.50	4.99	4.88	4.58	4.35	4.19	4.57
Caman	7.62	7.03	6.42	6.00	5.61	5.21	4.85	4.45	4.08	3.74	3.54	3.53	-	-	-	-	-	-	-	3.81
Neno	6.07	5.61	5.09	4.74	4.38	4.03	3.74	3.34	3.11	3.03	3.19	3.61	3.40	-	-	-	-	-	-	3.04
Minimum	1.62	1.53	1.47	1.39	1.31	1.22	1.09	1.04	0.89	0.93	0.81	0.71	0.84	0.79	0.73	0.68	0.62	2.22	3.73	0.81
Maximum	9.31	8.74	8.39	8.12	7.86	7.61	7.36	7.07	6.83	6.56	6.30	6.02	5.78	5.50	4.99	4.88	4.58	4.35	4.19	4.65
Average	4.81	4.49	4.25	4.03	3.81	3.58	3.38	3.19	3.00	2.90	2.76	2.80	3.18	3.31	3.14	3.06	3.02	3.55	3.96	2.40
Standard Deviation	2.75	2.61	2.48	2.38	2.29	2.19	2.11	2.04	1.96	1.86	1.81	1.75	1.66	1.45	1.47	1.44	1.40	1.16	0.32	1.37
Variants	7.55	6.82	6.13	5.66	5.24	4.78	4.46	4.15	3.83	3.46	3.28	3.05	2.77	2.09	2.15	2.07	1.97	1.34	0.10	1.89

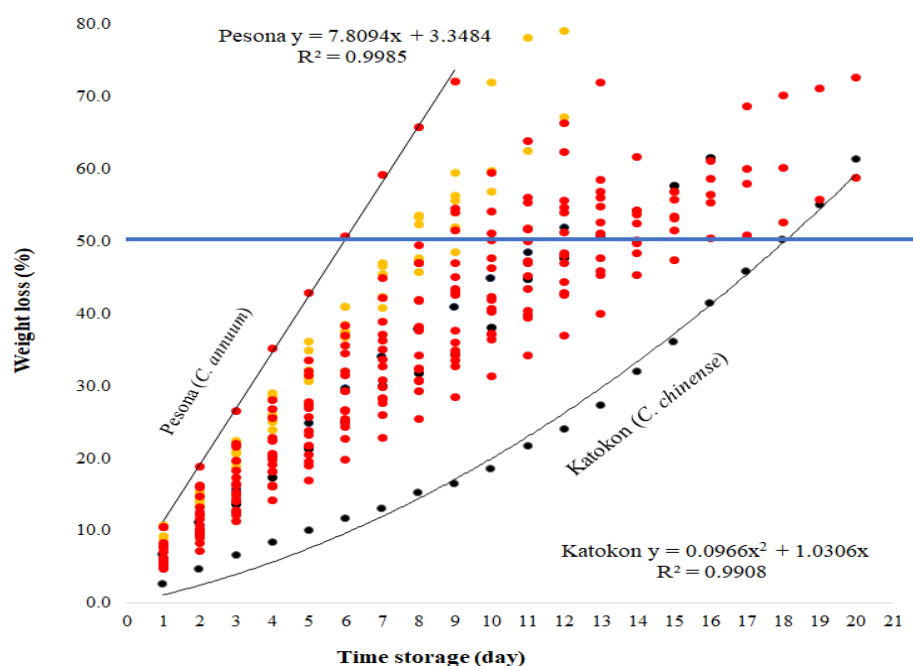


Figure 1. Percentage Fruit Weight Loss (FWL) per day during storage at room temperature. Shelf-life selection limit at 50% weight

Dry matter content, FWL, and soluble solids gained effects from the cultivar type and storage duration (Díaz-Pérez *et al.*, 2024). The dynamics of cuticle composition modification in the ripening and postharvest periods significantly varied among the cultivars (Lara *et al.*, 2019). The total amount of wax in the cuticle appeared to be high in chili fruits with rapid water loss (Kissinger *et al.*, 2005). The plant cuticle is an extracellular barrier that protects plant parts from the surrounding environment and plays important roles in plant growth and development. The cuticle's influence on the postharvest quality of fruits is a topic of current interest. The hypothesis was how loss of turgor and cuticle alters the fruit texture during ripening and after harvest (Lara *et al.*, 2019).

The chili fruits' weight decreased over time during storage at room temperature in different genotypes belonging to three distinct species (Figure 1). The percentage fruit weight loss (FWL) was significant from storage onset, with weight loss rate and pattern varying among the chili genotypes and species.

Genotypes with a long shelf life, such as Katokon, have a sloping pattern of fruit weight decline. The results revealed chili fruits with a steep and rapid fruit shrinkage rate lost more water than Katokon. The chili fruits' weight decreased with storage duration differing among the genotypes of each species. The six chili genotypes of the species *C. frutescens* revealed a similar response to these conditions. In contrast, the genotypes belonging to the species *C. annuum* and *C. chinense* showed wide variations. The significant decrease in fruit weight refers to the interaction of cultivar, maturity stage, and storage conditions in tomato fruits (Getinet *et al.*, 2008). The cuticular wax, lipoxygenase activity, and cell membrane ion leakage exhibited a direct association with the extent of postharvest water loss in chili fruits during storage (Kissinger *et al.*, 2005).

Chili fruits with a low degree of deterioration showed minimal transpiration water loss and relatively high cell turgor and limited cell wall metabolic variations (Lara *et al.*, 2019). Fruit water loss is a major problem

Table 3. Selection results of the chili genotypes for shelf life. Shelf-life criteria refer to the grouping results based on the Sturgess formula: Short (7–9 days), Moderate (10–12 days), Slightly long (13–15 days), and Long (16–19 days).

No.	Genotypes	Shelf life (days)	Categories
<i>Capsicum frutescens</i>			
1	Feira	8	Short
2	Bonita	8	Short
3	Pulai Pila	9	Short
4	RJHLxHIYUNG -7-25H	9	Short
5	RJHLxHIYUNG -7-28H	8	Short
6	ORI 212	7	Short
<i>Capsicum chinense</i>			
7	Peach Chupetinho	11	Moderate
8	Red Chupetinho	12	Moderate
9	Katokon	18	Long
<i>Capsicum annuum</i>			
10	Seroja	10	Moderate
11	Viola	10	Moderate
12	Arisa	11	Moderate
13	Adelina	15	Slightly Long
14	Fish Pepper	12	Moderate
15	Anies	12	Moderate
16	F5 136074xIMPERIAL -3-1-1	11	Slightly Long
17	F5 F6074xIMPERIAL -7-7-5	8	Short
18	F5 ANIESxBAJA -3-8-8	12	Moderate
19	F5 IMPERIALxF6136074 -2-1-1	11	Moderate
20	SSP	16	Long
21	Pesona	7	Short
22	Seloka	14	Slightly Long
23	Selekta	16	Long
24	Caman	8	Short
25	Neno	8	Short

for postharvest shelf life for the chili peppers destined for the fresh market (Do-Rêgo *et al.*, 2024). Fruit water loss, dry matter content, and soluble solids' content sustained most impacts from cultivar type and storage duration (Díaz-Pérez *et al.*, 2024). The fruit peduncle necrosis was considerably the earliest physiological parameter of chili pepper (*C. chinense*) fruit degradation during storage; however, it showed no correlation with other parameters used to monitor deterioration progression (Elibox *et al.*, 2015). Regulatory mechanisms may differ in fruit peduncle necrosis found in chili fruits during storage. The chili fruit with rapid water loss had elevated wax levels. The chili cuticle mainly consists of wax and cutin but also contains polysaccharides. A thick cuticle makes the fruit susceptible to cracking, causing water loss. However, cuticle monomers, individual

monomers, and wax components do not directly affect the water loss (Kissinger *et al.*, 2005).

The observation of FWL per day served to determine the shelf life of chili fruits (Table 2). Observations stopped when the FWL reached 50%. Shelf-life data of the 25 chili genotypes sustained grouping using the Sturgess formula, with the grouping results shown in Table 3. Based on these results, four categories of shelf-life level of chili fruits arose. Of the 25 genotypes, three genotypes have a long shelf life (Katokon, SSP, and Selekta); three genotypes have a slightly long shelf life; nine genotypes have a moderate shelf life; and 10 genotypes occurred with a short shelf life. The six genotypes of the species *C. frutescens* have a short shelf life. The species *C. chinense* group has one long shelf life genotype (Katokon), while the other two genotypes have

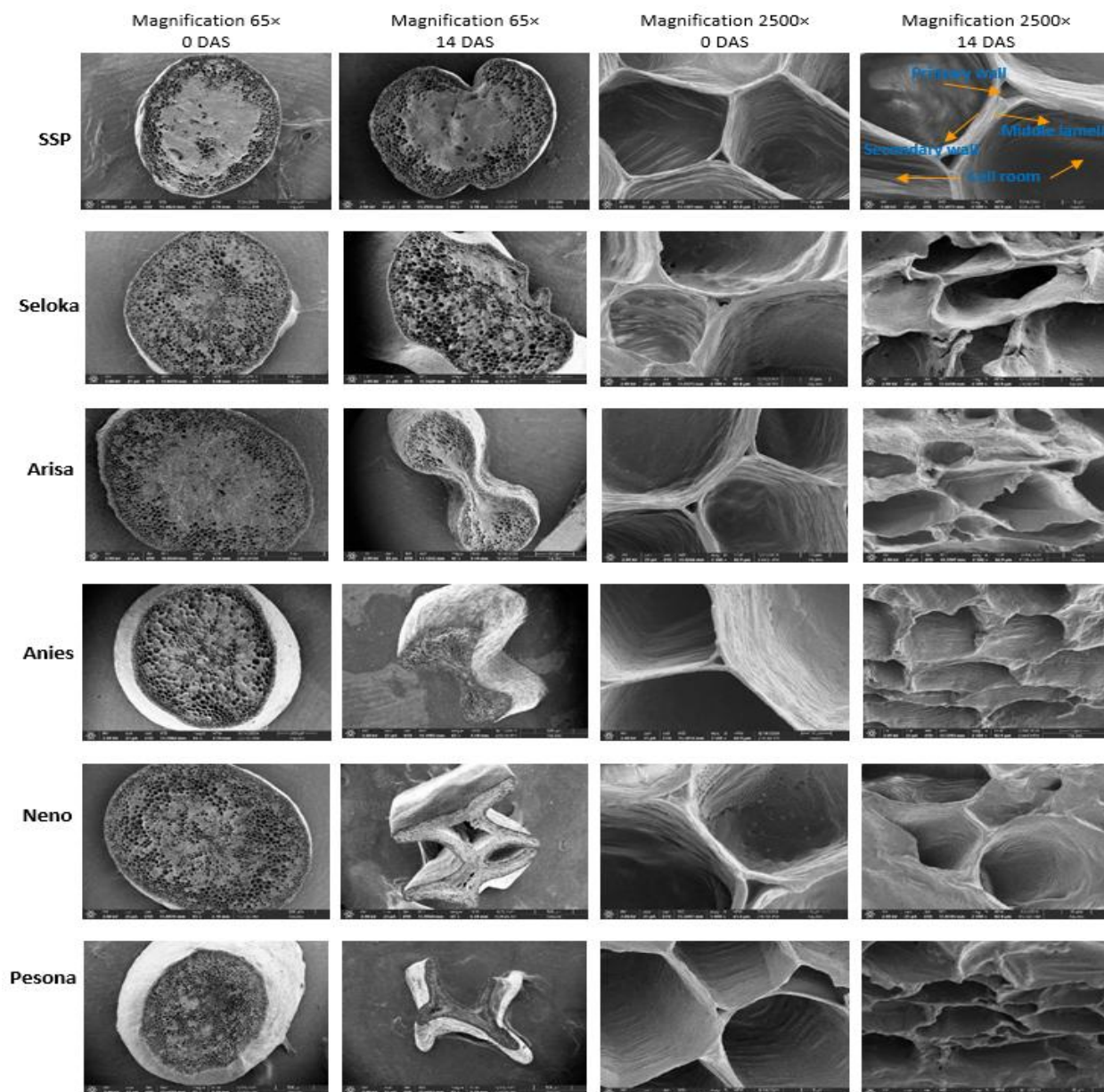


Figure 2. Cryo-SEM results of chili fruit before and after storage at room temperature at 65× and 2500× magnification. DAS: day after storage. SSP: long shelf life; Seloka: slightly long shelf life; Anies and Arisa: moderate shelf life; and Neno and Pesona: short shelf life.

a moderate shelf life. Genotype Katokon is the local chili pepper from Toraja, South Sulawesi, which is famous for being super spicy. SSP and Selektta are inbreds with wide cultivation in Indonesia. The species *C. annuum* has two long shelf life genotypes, namely, SSP (curly

red) and Selektta (large red); three slightly long shelf life genotypes (Adelina, Anies, and Seloka); and four short shelf life genotypes (Pesona, Caman, Neno, and F5 strain F6074XIMPERIAL-7-7-5).

Chili fruit cell structure variations after storage

Cryo-SEM analysis was successful on chili genotypes belonging to the species *C. annuum* because of observed shelf-life variability in this species group compared with the other two species. This analysis enclosed six *C. annuum* genotypes, both before and after storage, resulting in noticeable differences between them: SSP (long shelf life), Arisa (moderate shelf life), Seloka (slightly long shelf life), Anies (moderate shelf life), Neno (short shelf life), and Pesona (short shelf life). Fresh chili fruits were round and regular, and after 14 days, the fruit shrank (Figure 2). Storage conditions damaged cell walls and reduced the cell and tissue integration. Genotype SSP classified a 'long shelf life' classification, being resistant to these effects, thus maintaining its fruit tissue structure, unlike Pesona (classified as 'short shelf life'). The results suggested that genotype SPP showed the least water loss. However, further analysis is necessary to support these results. Water loss emerged as the main factor leading to fruit quality deterioration (Díaz-Pérez *et al.*, 2024). Storage conditions, especially temperature and RH, cause water loss from the chili fruits. Variations in the *Capsicum* fruit's cell walls affect the texture and become softer due to depolymerization of the pectin (Brummell, 2006).

Chili fruit water loss leads to decreased turgor pressure and reduced cell rigidity. Simultaneously, the fruit undergoes respiration and transpiration, using up sugar and water. These conditions result in various types of variations in the cells. This causes turgidity to decrease and weight loss, resulting in fruit shrinkage (Lufu *et al.* 2020). Chili genotypes susceptible to the high rates of water loss, membrane ion leakage, and lipoxygenase activity showed low amounts of total lipids, total phospholipids, and phospholipid classes (Maalekuu *et al.*, 2006). The limited fruit softening that occurs in *Capsicum* was ascribable to the decreased hemicellulose molecular weight and loss of pectin galactan side chains rather than pectin depolymerization (Harpster *et al.*, 2002).

Water loss causes damage from the skin to the pulp during storage. Skin cracking in chili peppers affects the fruit quality during temperature-dependent storage (Marinov *et al.* 2023). Chili pepper (*C. annuum* L.) fruits were naturally hollow, limiting water storage capacity; hence, small water losses result in a loss of freshness and firmness, reducing fruit quality, shelf life, and market value (Kissinger *et al.*, 2005). TEM (transmission electron microscopy) and SEM (scanning electron microscopy) analyses results revealed the skin cuticles of all pear varieties after 30 days of storage had severely damaged skin cellular structure, detached cuticles, damaged and degraded cell walls, and decreased electron density in the cell wall adhesive layer (Huo *et al.*, 2021). The SEM analysis of pomegranate peel's surfaces displayed lower peel thickness, more lenticels, larger lenticel size, and greater porosity, circularity, and roundness of lenticels observed at the calyx tips (Lufu *et al.*, 2021).

CONCLUSIONS

In chili (*Capsicum* sp.), the fruits' shelf life variability emerged to be dependent both on species and genotypes. A low percentage of weight loss indicates a slower rate of water loss, suggesting that extending the shelf life of the fruit is possible by reducing water loss. Three chili genotypes, Katokon, SSP, and Selektta, have been distinct with a prolonged shelf life, as indicated by a higher water content and reduced cell deterioration. Water loss during storage can lead to fruit cell decline and damage. Cultivars with prolonged shelf life demonstrate an ability to maintain the shape and structure of fruit cells and tissues during storage.

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