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Post-harvest quality and shelf-life of polyhouse grown cucumber as influenced by plant growth regulators, spacing and varietal difference

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Abstract
A study was conducted during the Rabi seasons of 2022-23 and 2023-24 at the Precision Farming Development Centre (PFDC), near Ram Dhan Seed Farm, CCS Haryana Agricultural University, Hisar (29°09′14.28″ N, 75°43′02.84″ E; 215 m amsl), situated in a semi-arid, subtropical climate. The experiment utilized a split-plot design with three replications. Main plots featured two cucumber varieties: Pusa Parthenocarpic Cucumber-6 (PPC-6) and Punjab Kheera-1 (PK-1). Sub-plots involved two plant spacings (60 × 60 cm and 60 × 45 cm), while sub-sub plots included treatments with plant growth regulators (PGRs): NAA (25 & 50 ppm), GA_3 (10 & 20 ppm), ethrel (100 & 200 ppm), combinations of ethrel + GA_3, NAA + GA_3, NAA + ethrel and a water-spray as control. PGRs were applied as foliar sprays at the two and four true leaf stages. Post-harvest losses of fruits were assessed under ambient conditions. PPC-6 demonstrated consistently lower post-harvest losses than Punjab Kheera-1 (PK-1) under both 60 × 60 cm and 60 × 45 cm spacing. Under the wider spacing, PPC-6 registered PLW of 10.87-11.05%, decay of 11.78-12.15%, and total loss of 22.65-23.20%, whereas PK-1 recorded slightly higher losses (PLW 10.95-11.14%, decay 11.91-12.26%, total 22.86-23.40%) during 2022-23 and 2023-24, respectively. Similar trends were observed at closer spacing. The combination treatment of NAA 20 ppm + GA_3 10 ppm delivered the lowest losses across all treatments. In contrast, the control (water spray) exhibited the highest losses (PLW 11.13-11.34%, decay 12.08-12.46%, total 23.21-23.79%). Storage duration exerted a marked effect: by day 12, PLW had doubled (~23.3%), decay surged to ~36.5%, and cumulative losses approached ~59% under both spacing regimes. Notably, interaction effects among variety, spacing and PGRs were largely non-significant. In conclusion, the integration of PPC-6 with foliar application of NAA 20 ppm + GA_3 10 ppm, especially at 60 × 60 cm spacing, is identified as the optimal strategy for minimizing post-harvest losses in polyhouse-grown cucumbers.

Keywords: Cucumber, polyhouse, PGRs, physiological loss in weight (PLW), decay loss, total loss

Introduction
Cucumber (*Cucumis sativus* L., 2n=14) is a globally important and economically valuable vegetable, cultivated extensively under protected conditions (El-Wanis *et al*., 2012) [12]. It bears yellow, unisexual flowers producing a pepo-type fruit. Native to Northern India, its wild progenitor *Cucumis sativus var*. *hardwickii* is found in the Himalayan foothills (Harlan, 1975 [14]; Pursglove, 1969) [24]. It is a monoecious, cross-pollinated vine with various sex forms (Bailey, 1969) [6], where male flowers precede female ones (Bantoc, 1964) [8]. Lateral tendrils and flower clusters form at leaf axils (Ahmed *et al*., 2004) [1]. Fruits are consumed fresh or pickled and harvested before physiological maturity (Kanellis *et al*., 1986 [17]; Chadha & Lal, 1993 [9]; Bairagi, 2013) [7]. Cucumber is nutritionally rich, containing 2.6 g carbohydrates, 0.6 g protein, 18 mg calcium, 0.02 mg thiamin, 0.02 mg riboflavin, 0.2 mg iron, 10 mg vitamin C, 0.01 mg niacin and 12 calories of energy per 100 g edible portion (Rashid, 1999) [26]. In India, cucumber is cultivated on 138.54 thousand hectares with a production of 1.99 million metric tons and productivity of 15.16 t/ha (Anonymous, 2024) [2]. Haryana alone accounts for 10.63 thousand hectares and 225.35 thousand metric tons of cucumber production, with 65.9% of protected cultivation area (~1236.2 ha) under cucumber (Anonymous, 2024a) [3].

Under ambient conditions (approximately 29-33 °C, 65-70 % RH), unwrapped cucumbers typically remain marketable for only 2-5 days, after which they exhibit significant quality deterioration such as moisture loss, shriveling, yellowing, firmness loss and decay rendering them unmarketable. Furthermore, research under ambient conditions at similar temperatures confirms crispness and firmness decline steadily over 3-5 days, aligning with measurements of physiological weight loss, texture degradation and declining total soluble solids and acidity. Due to increased demand, cucumber is now cultivated globally under field and greenhouse systems. Greenhouses enhance plant growth by trapping solar radiation and optimizing temperature distribution (Tiwari, 2006 [33]; Sauser *et al*., 1998) [30]. Additionally, CO_2 concentration and photosynthetically active radiation (PAR) are crucial factors influencing growth under protected environments (Navale *et al*., 2003) [21].

Parthenocarpic varieties are particularly advantageous due to their ability to set fruit without pollination an important trait in greenhouses where pollinators are scarce (Rawat *et al*., 2014) [27]. Gynoecious varieties, which predominantly bear female flowers, are also widely used in commercial production for higher fruit yield. Bio-active substances such as PGRs enhance physiological processes, homeostasis and stress resistance (Voronina, 2008 [35]; Prusakova & Chizhova, 2005 [23]; Sheudzhen *et al*., 2012) [31]. Cucumber exhibits diverse floral morphologies, including staminate, pistillate and hermaphrodite flowers (Thappa *et al*., 2011) [32]. Exogenous PGR application especially during the two or four leaf stages can influence sex expression, shifting it toward femaleness and increasing pistillate flower numbers, fruit set, fruit weight and total yield (Vadigeri *et al*., 2001 [34]; Rafeekher *et al*., 2002 [25]; Mia *et al*., 2014 [19]; Hossain *et al*., 2006) [15]. Moreover, PGRs are considered safe and non-toxic, offering a sustainable tool for boosting yield and food safety (Ghani *et al*., 2013) [13]. Optimizing plant density is another critical component in greenhouse cucumber production, as it maximizes space and nutrient use (Lal *et al*., 2014) [18]. Dense foliage may cause fruit shading, resulting in pale coloration, hence appropriate spacing ensures sufficient light and airflow for optimal development.

Materials and Methods

The experiment was conducted during *Rabi* seasons of 2022-23 and 2023-24 under polyhouse conditions at the Precision Farming Development Centre (PFDC), located near Ram Dhan Seed Farm, CCS Haryana Agricultural University, Hisar (29°09′14.28″ N, 75°43′02.84″ E; 215 m amsl). The site falls under a semi-arid, subtropical climate zone. The study employed a split-plot design with three replications. Main plots included two cucumber varieties: Pusa Parthenocarpic Cucumber-6 (PPC-6) and Punjab Kheera-1 (PK-1). Sub-plots consisted of two plant spacings (60 × 60 cm and 60 × 45 cm) and sub sub plot includes three plant growth regulators and their combinations: NAA (25 & 50 ppm), GA_3 (10 & 20 ppm), ethrel (100 & 200 ppm) and combinations of ethrel + GA_3, NAA + GA_3, NAA + ethrel along with a water-spray control. PGRs were applied as foliar sprays at the two and four true leaf stages. Fruits were evaluated for post-harvest losses under ambient conditions. The data collected pertaining to various parameters was subjected to statistical analysis utilizing OPSTAT software, which was developed by Chaudhary Charan Singh Haryana Agricultural University, Hisar, to ascertain the significance of the variations induced by the experimental treatments. All significance tests were conducted at a 5% level of significance. Parameters included:

Physiological loss in weight-PLW (%)

The weight of the fruit in each treatment was recorded at alternate days and subtracted from the initial weight. The loss of weight in grams in relation to initial weight was calculated and expressed as percentage.

$$\text{Decay Loss (\%)} = \frac{\text{Initial Fruit Weight} - \text{Fruit Weight on the Day of Observation}}{\text{Initial Fruit Weight}} \times 100$$

Decay percentage of the total fruit was calculated by dividing the decaying fruit weight (g) by the initial fruit weight (g) using the formula given below:

$$\text{Decay loss (\%)} = \frac{\text{Decaying fruit weight (g)}}{\text{Initial fruit weight (g)}} \times 100$$

Total loss (%)

The total loss was calculated by combining of physiological and decay losses which results in a significant reduction in the marketable quantity and quality of cucumbers, impacting the entire supply chain.

Total loss (%) = Physiological loss in weight (%) + decay loss (%)

Results

1. Physiological loss in weight (%) at wider (60 x 60 cm) and closer (60 × 45 cm) spacing

Results of Table 1 & 2 revealed the effect of varieties and PGRs on physiological loss in weight of polyhouse cucumber (60 x 60 cm) & (60 × 45 cm) at room temperature.

1.1 Effect of varieties on physiological loss in weight at wider and closer spacing

During the year 2022-23, the mean PLW was 10.87% in PPC-6 and 10.95% in PK-1 at wider spacing while, the average PLW was 10.90% for PPC-6 and 11.02% for PK-1 at closer spacing. In 2023-24, these values increased slightly to 11.05% and 11.14%, respectively at wider spacing. A similar trend was observed in 2023-24, where PLW increased slightly to 11.08% in PPC-6 and 11.17% in PK-1 at closer spacing. The difference between varieties was found to be statistically significant, with a critical difference (CD) at 5% of 0.07 & 0.08 in 2022-23 and 0.06 & 0.06 in 2023-24 at wider and closer spacing, respectively.

1.2 Effect of plant growth regulators on physiological loss in weight at wider and closer spacing

Among all treatments, the lowest mean of PLW was observed with NAA @ 20 ppm + GA_3 @ 10 ppm, recording 10.71% & 10.76% in 2022-23 and 10.90% & 10.92% in 2023-24 at wider and closer spacing, respectively. This was closely followed by the combination NAA @ 25 ppm + ethrel @ 100 ppm. In contrast, the control treatment exhibited the highest PLW, with values of 11.13% & 11.18% in 2022-23 and 11.31% & 11.34% in 2023-24, respectively. The overall effect of PGRs was statistically significant in both years.

1.3 Effect of storage duration on physiological loss in weight at wider and closer spacing

Across all treatments and varieties, PLW increased steadily with time. At 0 days, no weight loss was recorded in both spacing. By 3 days, PLW reached 4.40% & 4.46% in 2022-23 and 5.00% & 5.02% in 2023-24 at wider and closer spacing, respectively. It continued to rise through 6 days (8.63% and 9.25%) & (8.67% and 9.26%) and 9 days (18.79% and 17.98%) & 18.86% and (18.03%), reaching the maximum values at 12 days with 22.74% & 22.81% in 2022-23 and 23.25% & 23.31% in 2023-24 at wider and closer spacing, respectively. Storage period had a pronounced and progressive effect on the PLW of cucumber fruits. These trends confirm that weight loss during storage is time-dependent and inevitable.

1.4 Interaction effect on physiological loss in weight at wider and closer spacing

The interactions between varieties and PGRs, PGRs and storage and the three-way interaction of variety × PGR × storage were found to be non-significant in both years.

2. Decay loss (%) of cucumber at wider (60 x 60 cm) and closer (60 × 45 cm) spacing

Decay loss (%) of cucumber fruits was observed to be influenced significantly by variety, plant growth regulator treatments and storage duration under polyhouse conditions at wider and closer spacing given in Table 3 & Table 4.

2.1 Effect of varieties on decay loss (%) of cucumber at wider and closer spacing

A comparison between the two cucumber varieties revealed that PPC-6 experienced slightly lower decay loss than PK-1 across both years. In 2022-23, the mean decay loss for PPC-6 was 11.78% & 11.85%, while PK-1 recorded 11.91% & 11.97% at wider and closer spacing, respectively. The trend remained consistent in 2023-24. The difference between varieties was statistically significant. Despite the minimal varietal difference, PPC-6 showed a slight advantage in post-harvest retention.

2.2 Effect of plant growth regulators on decay loss (%) of cucumber at wider and closer spacing

The lowest decay loss was recorded with NAA @ 20 ppm + GA_3 @ 10 ppm, which showed mean values of 11.61% & 11.65% in 2022-23 and 11.99% & 12.05% in 2023-24 at wider and closer spacing, respectively. This was closely followed by NAA @ 25 ppm + ethrel @ 100 ppm. In contrast, the control treatment exhibited the highest decay loss, registering 12.08% & 12.14% in 2022-23 and 12.40% & 12.46% in 2023-24 at wider and closer spacing, respectively. The effect of PGRs was statistically significant in both years.

2.3 Effect of storage duration on decay loss (%) of cucumber at wider and closer spacing

Decay loss of cucumber increased progressively with storage time across all treatments. On 0 and 3 days, no decay loss was observed in both spacing. By 6 days, average decay loss rose to 8.09% & 8.22% in 2022-23 and 8.69% & 8.74% in 2023-24 at wider and closer spacing, respectively. The decay continued to increase steadily, reaching 15.37% & 15.45% and 15.86% & 15.94% at 9 days and finally peaked at 12 days with 35.76% & 35.87% and 36.47% & 36.58%, respectively. These results reflect a typical decay progression pattern during post-harvest storage and highlight the need for timely marketing or cold storage to reduce losses.

2.4 Interaction effects on decay loss (%) of cucumber at wider and closer spacing

The interaction between varieties and PGRs, as well as PGRs with storage duration and the three-way interaction (variety × PGR × storage) were non-significant in both years.

3. Total loss (%) of cucumber at wider (60 x 60 cm) and closer (60 × 45 cm) spacing

Table 5 & Table 6, detailing the effect of varieties and plant growth regulators (PGRs) on total loss (%) of cucumber under polyhouse conditions at wider and closer spacing during the years 2022-23 and 2023-24.

3.1 Effect of varieties on total loss (%) of cucumber at wider and closer spacing

In both years, PK-1 exhibited slightly higher total loss (%) than PPC-6. In 2022-23, the mean total loss was 22.65% & 22.75% for PPC-6 and 22.86% & 22.99% for PK-1 at wider and closer spacing, respectively. Similarly, in 2023-24, the respective mean increased. These differences were statistically significant, with the CD at 5%.

3.2 Effect of plant growth regulators on total loss (%) of cucumber at wider and closer spacing

Among all treatments, the lowest total loss in 2022-23 was recorded with the application of NAA @ 20 ppm + GA_3 @ 10 ppm, with a mean of 22.32% & 22.41%, followed closely by NAA @ 25 ppm + ethrel @ 100 ppm (22.40% & 22.51%) and ethrel @ 100 ppm + GA_3 @ 10 ppm (22.51% & 22.61%) at wider and closer spacing, respectively. In the subsequent season (2023-24), the trend remained consistent, with NAA @ 20 ppm + GA_3 @ 10 ppm again showing the minimum total loss 22.89% & 22.97%, followed by NAA @ 25 ppm + ethrel @ 100 ppm (22.97% & 23.03%) and ethrel @ 100 ppm + GA_3 @ 10 ppm (23.07% & 23.16%) at wider and closer spacing, respectively. The control treatment again registered the maximum loss. The differences among PGR treatments were statistically significant in both years.

3.3 Effect of storage duration on total loss (%) of cucumber at wider and closer spacing

Storage duration had a direct and profound impact on total loss percentages. Initially (0 day), no loss was recorded. However, by 3rd day, total loss had increased to 4.40% & 4.46% (2022-23) and 5.00% & 5.02% (2023-24) at wider and closer spacing, respectively. A sharp rise was noted by the 6th day, with losses reaching 16.71% & 16.89% and 17.93% & 18%, respectively. On the 9th day, losses peaked to 34.15% & 34.31% (2022-23) and 33.84% & 33.96% (2023-24) and by the 12th day, total loss was 58.50% & 58.69% in 2022-23 and 59.72% & 59.89% in 2023-24 at wider and closer spacing, respectively. The total loss increased markedly with longer storage durations.

3.4 Interaction effects on total loss (%) of cucumber at wider and closer spacing

Most interaction effects such as varieties × PGRs, PGRs × storage and varieties × PGRs × storage were non-significant.

Table 1: Effect of varieties, spacing and PGRs on physiological loss in weight (%) of cucumber under polyhouse at wider spacing (60 x 60 cm)

Plant growth regulators	2022-23											2023-24										
	Pusa Parthenocarpic Cucumber-6					Punjab Kheera-1						Pusa Parthenocarpic Cucumber-6					Punjab Kheera-1					
	0 day	3 day	6 day	9 day	12 day	0 day	3 day	6 day	9 day	12 day	Mean storage	0 day	3 day	6 day	9 day	12 day	0 day	3 day	6 day	9 day	12 day	Mean storage
NAA @ 25 ppm	0.00	4.34	8.56	18.66	22.62	0.00	4.42	8.65	18.83	22.79	10.89	0.00	4.91	9.16	17.85	23.11	0.00	5.01	9.27	18.02	23.29	11.06
NAA @ 50 ppm	0.00	4.32	8.55	18.62	22.57	0.00	4.36	8.60	18.75	22.69	10.85	0.00	4.91	9.16	17.82	23.05	0.00	4.96	9.21	17.93	23.22	11.03
GA3 @ 10 ppm	0.00	4.45	8.66	18.83	22.80	0.00	4.51	8.72	18.95	22.90	10.98	0.00	5.02	9.27	18.00	23.26	0.00	5.11	9.36	18.15	23.42	11.16
GA3 @ 20 ppm	0.00	4.40	8.63	18.74	22.71	0.00	4.47	8.72	18.91	22.87	10.95	0.00	4.98	9.24	17.93	23.19	0.00	5.03	9.31	18.08	23.34	11.11
Ethrel @ 100 ppm	0.00	4.45	8.67	18.89	22.86	0.00	4.53	8.75	19.02	22.95	11.01	0.00	5.03	9.27	18.06	23.31	0.00	5.17	9.41	18.25	23.52	11.20
Ethrel @ 200 ppm	0.00	4.47	8.69	18.97	22.92	0.00	4.59	8.80	19.10	23.05	11.06	0.00	5.10	9.34	18.18	23.39	0.00	5.15	9.42	18.29	23.57	11.24
Ethrel @ 100 ppm + GA3 @ 10 ppm	0.00	4.27	8.49	18.52	22.45	0.00	4.32	8.56	18.70	22.66	10.80	0.00	4.88	9.12	17.71	23.00	0.00	4.94	9.19	17.89	23.16	10.99
NAA @ 20 ppm + GA3 @ 10 ppm	0.00	4.20	8.42	18.37	22.32	0.00	4.26	8.49	18.54	22.49	10.71	0.00	4.79	9.04	17.57	22.87	0.00	4.85	9.12	17.73	23.01	10.90
NAA @ 25 ppm + ethrel @ 100 ppm	0.00	4.21	8.42	18.42	22.39	0.00	4.28	8.51	18.61	22.53	10.74	0.00	4.80	9.05	17.63	22.92	0.00	4.90	9.16	17.82	23.11	10.94
Control (water spray)	0.00	4.55	8.75	19.08	23.03	0.00	4.65	8.86	19.20	23.15	11.13	0.00	5.16	9.38	18.27	23.53	0.00	5.25	9.48	18.39	23.67	11.31
Mean varieties x storage	0.00	4.37	8.58	18.71	22.67	0.00	4.44	8.67	18.86	22.81		0.00	4.96	9.20	17.90	23.16	0.00	5.04	9.29	18.05	23.33	
Mean storage	0.00		4.40		8.63		18.79		22.74			0.00		5.00		9.25		17.98		23.25		
Mean varieties	10.87					10.95						11.05					11.14					
Factors	CD at 5%		SE (m)			Factors	CD at 5%		SE (m)			Factors	CD at 5%		SE (m)		Factors	CD at 5%		SE (m)		
Varieties	0.07		0.04			storage	0.11		0.04			Varieties	0.06		0.02		storage	0.09		0.03		
PGRs	0.15		0.08			Varieties x PGRs	NS		0.06			PGRs	0.13		0.05		Varieties x PGRs	NS		0.05		
Varieties x PGRs	NS		0.11			Storage x PGRs	NS		0.12			Varieties x PGRs	NS		0.07		Storage x PGRs	NS		0.11		
Varieties x PGRs x storage	NS		0.17									Varieties x PGRs x storage	NS		0.15							

Table 2: Effect of varieties and plant growth regulators on physiological loss in weight (%) of cucumber under polyhouse at closer spacing (45 x 45 cm)

Plant growth regulators	2022-23											2023-24										
	Pusa Parthenocarpic Cucumber-6					Punjab Kheera-1						Pusa Parthenocarpic Cucumber-6					Punjab Kheera-1					
	0 day	3 day	6 day	9 day	12 day	0 day	3 day	6 day	9 day	12 day	Mean storage	0 day	3 day	6 day	9 day	12 day	0 day	3 day	6 day	9 day	12 day	Mean storage
NAA @ 25 ppm	0.00	4.38	8.59	18.76	22.70	0.00	4.47	8.70	18.88	22.83	10.93	0.00	4.96	9.23	17.96	23.19	0.00	5.04	9.29	18.04	23.34	11.11
NAA @ 50 ppm	0.00	4.38	8.58	18.70	22.67	0.00	4.46	8.67	18.84	22.77	10.91	0.00	4.93	9.16	17.86	23.14	0.00	5.02	9.27	18.01	23.31	11.07
GA3 @ 10 ppm	0.00	4.44	8.65	18.90	22.85	0.00	4.58	8.78	19.05	23.01	11.03	0.00	5.02	9.27	18.08	23.31	0.00	5.13	9.38	18.20	23.52	11.19
GA3 @ 20 ppm	0.00	4.41	8.62	18.85	22.80	0.00	4.55	8.76	18.99	22.93	10.99	0.00	4.98	9.23	18.03	23.25	0.00	5.08	9.32	18.12	23.44	11.14
Ethrel @ 100 ppm	0.00	4.49	8.72	19.00	22.93	0.00	4.63	8.80	19.10	23.04	11.07	0.00	5.09	9.34	18.18	23.40	0.00	5.16	9.39	18.27	23.57	11.24
Ethrel @ 200 ppm	0.00	4.50	8.72	19.05	22.99	0.00	4.67	8.86	19.17	23.13	11.11	0.00	5.09	9.34	18.23	23.47	0.00	5.18	9.40	18.29	23.60	11.26
Ethrel @ 100 ppm + GA3 @ 10 ppm	0.00	4.29	8.52	18.57	22.52	0.00	4.39	8.62	18.76	22.69	10.84	0.00	4.89	9.15	17.77	23.08	0.00	4.93	9.21	17.91	23.19	11.01
NAA @ 20 ppm + GA3 @ 10 ppm	0.00	4.23	8.45	18.43	22.39	0.00	4.34	8.56	18.63	22.58	10.76	0.00	4.79	9.05	17.61	22.92	0.00	4.87	9.14	17.78	23.06	10.92
NAA @ 25 ppm + ethrel @ 100 ppm	0.00	4.24	8.47	18.48	22.43	0.00	4.38	8.60	18.72	22.67	10.80	0.00	4.83	9.08	17.66	22.99	0.00	4.88	9.12	17.82	23.09	10.95
Control (water spray)	0.00	4.56	8.78	19.11	23.07	0.00	4.73	8.94	19.30	23.26	11.18	0.00	5.19	9.42	18.31	23.55	0.00	5.27	9.48	18.41	23.72	11.34
Mean varieties x storage	0.00	4.39	8.61	18.79	22.74	0.00	4.52	8.73	18.94	22.89		0.00	4.98	9.23	17.97	23.23	0.00	5.06	9.30	18.08	23.38	
Mean storage	0.00		4.46		8.67		18.86		22.81			0.00		5.02		9.26		18.03		23.31		
Mean varieties	10.90					11.02						11.08					11.17					
Factors	CD at 5%		SE (m)			Fcators	CD at 5%		SE (m)			Factors	CD at 5%		SE (m)		Factors	CD at 5%		SE (m)		
Varieties	0.08		0.03			storage	0.13		0.05			Varieties	0.06		0.02		storage	0.10		0.03		
PGRs	0.18		0.06			Varieties x PGRs	NS		0.06			PGRs	0.14		0.05		Varieties x PGRs	NS		0.05		
Varieties x PGRs	NS		0.09			Storage x PGRs	NS		0.14			Varieties x PGRs	NS		0.07		Storage x PGRs	NS		0.11		
Varieties x PGRs x storage	NS		0.20									Varieties x PGRs x storage	NS		0.15							

Table 3: Effect of varieties and plant growth regulators on decay loss (%) of cucumber under polyhouse at wider spacing (60 x 60 cm)

Plant growth regulators	2022-23											2023-24										
	Pusa Parthenocarpic Cucumber-6					Punjab Kheera-1						Pusa Parthenocarpic Cucumber-6					Punjab Kheera-1					
	0 day	3 day	6 day	9 day	12 day	0 day	3 day	6 day	9 day	12 day	Mean storage	0 day	3 day	6 day	9 day	12 day	0 day	3 day	6 day	9 day	12 day	Mean storage
NAA @ 25 ppm	0.00	0.00	7.95	15.27	35.57	0.00	0.00	8.16	15.42	35.87	11.82	0.00	0.00	8.58	15.78	36.32	0.00	0.00	8.76	15.94	36.59	12.20
NAA @ 50 ppm	0.00	0.00	7.92	15.23	35.52	0.00	0.00	8.06	15.34	35.76	11.78	0.00	0.00	8.51	15.68	36.21	0.00	0.00	8.63	15.83	36.47	12.13
GA3 @ 10 ppm	0.00	0.00	8.09	15.35	35.72	0.00	0.00	8.30	15.55	36.08	11.91	0.00	0.00	8.74	15.88	36.45	0.00	0.00	8.89	16.03	36.80	12.28
GA3 @ 20 ppm	0.00	0.00	8.03	15.32	35.66	0.00	0.00	8.20	15.46	35.95	11.86	0.00	0.00	8.65	15.82	36.34	0.00	0.00	8.81	16.00	36.71	12.23
Ethrel @ 100 ppm	0.00	0.00	8.20	15.44	35.83	0.00	0.00	8.40	15.66	36.21	11.97	0.00	0.00	8.86	15.97	36.57	0.00	0.00	9.01	16.14	36.92	12.35
Ethrel @ 200 ppm	0.00	0.00	8.27	15.50	35.92	0.00	0.00	8.45	15.69	36.26	12.01	0.00	0.00	8.92	16.03	36.67	0.00	0.00	8.94	16.08	36.86	12.35
Ethrel @ 100 ppm + GA3 @ 10 ppm	0.00	0.00	7.80	15.13	35.38	0.00	0.00	7.94	15.24	35.61	11.71	0.00	0.00	8.44	15.63	36.08	0.00	0.00	8.54	15.79	36.35	12.08
NAA @ 20 ppm + GA3 @ 10 ppm	0.00	0.00	7.65	15.00	35.18	0.00	0.00	7.79	15.10	35.40	11.61	0.00	0.00	8.33	15.53	35.92	0.00	0.00	8.36	15.62	36.16	11.99
NAA @ 25 ppm + ethrel @ 100 ppm	0.00	0.00	7.70	15.04	35.27	0.00	0.00	7.88	15.19	35.55	11.66	0.00	0.00	8.33	15.55	36.03	0.00	0.00	8.44	15.69	36.23	12.03
Control (water spray)	0.00	0.00	8.35	15.65	36.08	0.00	0.00	8.57	15.79	36.40	12.08	0.00	0.00	8.94	16.12	36.79	0.00	0.00	9.02	16.17	37.01	12.40
Mean varieties x storage	0.00	0.00	8.00	15.29	35.61	0.00	0.00	8.18	15.44	35.91		0.00	0.00	8.63	15.80	36.34	0.00	0.00	8.74	15.93	36.61	
Mean storage	0.00		0.00		8.09	15.37			35.76			0.00		0.00		8.69	15.86			36.47		
Mean varieties	11.78					11.91						12.15					12.26					
Factors	CD at 5%		SE (m)			Factors	CD at 5%		SE (m)			Factors		CD at 5%	SE (m)		Factors		CD at 5%	SE (m)		
Varieties	0.08		0.03			storage	0.13		0.05			Varieties		0.08	0.03		Storage		0.13	0.05		
PGRs	0.19		0.07			Varieties x PGRs	NS		0.07			PGRs		0.18	0.06		Varieties x PGRs		NS	0.06		
Varieties x PGRs	NS		0.09			Storage x PGRs	NS		0.15			Varieties x PGRs		NS	0.09		Storage x PGRs		NS	0.14		
Varieties x PGRs x storage	NS		0.21									Varieties x PGRs x storage		NS	0.20							

Table 4: Effect of varieties and plant growth regulators on decay loss (%) of cucumber under polyhouse at closer spacing (45 x 45 cm)

Plant growth regulators (4)	2022-23											2023-24										
	Pusa Parthenocarpic Cucumber-6					Punjab Kheera-1						Pusa Parthenocarpic Cucumber-6					Punjab Kheera-1					
	0 day	3 day	6 day	9 day	12 day	0 day	3 day	6 day	9 day	12 day	Mean storage	0 day	3 day	6 day	9 day	12 day	0 day	3 day	6 day	9 day	12 day	Mean storage
NAA @ 25 ppm	0.00	0.00	8.12	15.39	35.72	0.00	0.00	8.32	15.52	36.00	11.91	0.00	0.00	8.68	15.86	36.40	0.00	0.00	8.80	16.00	36.71	12.24
NAA @ 50 ppm	0.00	0.00	8.01	15.31	35.61	0.00	0.00	8.23	15.46	35.94	11.86	0.00	0.00	8.59	15.80	36.28	0.00	0.00	8.70	15.94	36.65	12.20
GA3 @ 10 ppm	0.00	0.00	8.28	15.49	35.91	0.00	0.00	8.48	15.63	36.19	12.00	0.00	0.00	8.78	15.93	36.58	0.00	0.00	8.89	16.08	36.86	12.31
GA3 @ 20 ppm	0.00	0.00	8.18	15.39	35.78	0.00	0.00	8.37	15.57	36.07	11.94	0.00	0.00	8.71	15.87	36.46	0.00	0.00	8.85	16.07	36.73	12.27
Ethrel @ 100 ppm	0.00	0.00	8.34	15.55	36.00	0.00	0.00	8.57	15.69	36.30	12.05	0.00	0.00	8.91	16.03	36.69	0.00	0.00	8.91	16.07	36.91	12.35
Ethrel @ 200 ppm	0.00	0.00	8.40	15.60	36.05	0.00	0.00	8.62	15.72	36.33	12.07	0.00	0.00	8.99	16.13	36.76	0.00	0.00	8.99	16.15	36.99	12.40
Ethrel @ 100 ppm + GA3 @ 10 ppm	0.00	0.00	7.87	15.20	35.46	0.00	0.00	8.11	15.35	35.78	11.78	0.00	0.00	8.52	15.75	36.21	0.00	0.00	8.59	15.86	36.51	12.14
NAA @ 20 ppm + GA3 @ 10 ppm	0.00	0.00	7.67	15.04	35.26	0.00	0.00	7.85	15.14	35.49	11.65	0.00	0.00	8.36	15.61	36.03	0.00	0.00	8.45	15.73	36.30	12.05
NAA @ 25 ppm + ethrel @ 100 ppm	0.00	0.00	7.79	15.15	35.38	0.00	0.00	7.95	15.22	35.62	11.71	0.00	0.00	8.40	15.64	36.13	0.00	0.00	8.49	15.78	36.40	12.08
Control (water spray)	0.00	0.00	8.51	15.69	36.15	0.00	0.00	8.75	15.82	36.46	12.14	0.00	0.00	9.02	16.19	36.89	0.00	0.00	9.09	16.26	37.14	12.46
Mean varieties x storage	0.00	0.00	8.12	15.38	35.73	0.00	0.00	8.32	15.51	36.02		0.00	0.00	8.70	15.88	36.44	0.00	0.00	8.78	15.99	36.72	
Mean storage	0.00		0.00		8.22	15.45			35.87			0.00		0.00		8.74	15.94			36.58		
Mean varieties	11.85					11.97						12.20					12.30					
Factors	CD at 5%		SE (m)			Factors	CD at 5%		SE (m)			Factors		CD at 5%	SE (m)		Factors		CD at 5%	SE (m)		
Varieties	0.10		0.04			storage	0.16		0.06			Varieties		NS	0.03		Storage		0.15	0.06		
PGRs	0.22		0.08			Varieties x PGRs	NS		0.08			PGRs		0.22	0.08		Varieties x PGRs		NS	0.08		
Varieties x PGRs	NS		0.11			Storage x PGRs	NS		0.18			Varieties x PGRs		NS	0.11		Storage x PGRs		NS	0.17		
Varieties x PGRs x storage	NS		0.25									Varieties x PGRs x storage		NS	0.24							

Table 5: Effect of varieties and plant growth regulators on total loss (%) of cucumber under polyhouse at wider spacing (60 x 60 cm)

Plant growth regulators	2022-23											2023-24										
	Pusa Parthenocarpic Cucumber-6					Punjab Kheera-1						Pusa Parthenocarpic Cucumber-6					Punjab Kheera-1					
	0 day	3 day	6 day	9 day	12 day	0 day	3 day	6 day	9 day	12 day	Mean storage	0 day	3 day	6 day	9 day	12 day	0 day	3 day	6 day	9 day	12 day	Mean storage
NAA @ 25 ppm	0.00	4.34	16.50	33.92	58.18	0.00	4.42	16.81	34.25	58.66	22.71	0.00	4.91	17.75	33.63	59.44	0.00	5.01	18.03	33.96	59.88	23.26
NAA @ 50 ppm	0.00	4.32	16.47	33.85	58.09	0.00	4.36	16.66	34.09	58.46	22.63	0.00	4.91	17.67	33.50	59.26	0.00	4.96	17.84	33.76	59.68	23.16
GA3 @ 10 ppm	0.00	4.45	16.75	34.18	58.52	0.00	4.51	17.02	34.50	58.98	22.89	0.00	5.02	18.01	33.88	59.71	0.00	5.11	18.25	34.17	60.22	23.44
GA3 @ 20 ppm	0.00	4.40	16.66	34.06	58.37	0.00	4.47	16.92	34.37	58.82	22.81	0.00	4.98	17.89	33.74	59.53	0.00	5.03	18.12	34.08	60.06	23.34
Ethrel @ 100 ppm	0.00	4.45	16.87	34.33	58.69	0.00	4.53	17.15	34.69	59.16	22.99	0.00	5.03	18.13	34.03	59.88	0.00	5.17	18.42	34.39	60.45	23.55
Ethrel @ 200 ppm	0.00	4.47	16.96	34.47	58.84	0.00	4.59	17.25	34.79	59.31	23.07	0.00	5.10	18.26	34.21	60.06	0.00	5.15	18.36	34.37	60.43	23.59
Ethrel @ 100 ppm + GA3 @ 10 ppm	0.00	4.27	16.29	33.65	57.83	0.00	4.32	16.50	33.94	58.27	22.51	0.00	4.88	17.56	33.34	59.08	0.00	4.94	17.74	33.68	59.52	23.07
NAA @ 20 ppm + GA3 @ 10 ppm	0.00	4.20	16.07	33.37	57.50	0.00	4.26	16.27	33.64	57.89	22.32	0.00	4.79	17.37	33.10	58.79	0.00	4.85	17.49	33.36	59.18	22.89
NAA @ 25 ppm + ethrel @ 100 ppm	0.00	4.21	16.12	33.46	57.66	0.00	4.28	16.39	33.80	58.07	22.40	0.00	4.80	17.39	33.18	58.94	0.00	4.90	17.60	33.51	59.34	22.97
Control (water spray)	0.00	4.55	17.10	34.73	59.11	0.00	4.65	17.43	34.99	59.55	23.21	0.00	5.16	18.32	34.40	60.33	0.00	5.25	18.50	34.56	60.68	23.72
Mean varieties x storage	0.00	4.37	16.58	34.00	58.28	0.00	4.44	16.84	34.31	58.72		0.00	4.96	17.84	33.70	59.50	0.00	5.04	18.03	33.98	59.94	
Mean storage	0.00		4.40		16.71	34.15			58.50			0.00		5.00		17.93	33.84			59.72		
Mean varieties	22.65					22.86						23.20					23.40					
Factors	CD at 5%		SE (m)			Fcators	CD at 5%		SE (m)			Factors	CD at 5%	SE (m)			Factors	CD at 5%	SE (m)			
Varieties	0.12		0.04			storage	0.18		0.07			Varieties	0.10	0.04			Storage	0.16	0.06			
PGRs	0.26		0.09			Varieties x PGRs	NS		0.09			PGRs	0.22	0.08			Varieties x PGRs	0.22	0.08			
Varieties x PGRs	NS		0.13			Storage x PGRs	NS		0.21			Varieties x PGRs	NS	0.11			Storage x PGRs	NS	0.18			
Varieties x PGRs x storage	NS		0.29									Varieties x PGRs x storage	NS	0.20								

Table 6: Effect of varieties and plant growth regulators on total loss (%) of cucumber under polyhouse at closer spacing (45 x 45 cm)

Plant growth regulators	2022-23											2023-24										
	Pusa Parthenocarpic Cucumber-6					Punjab Kheera-1						Pusa Parthenocarpic Cucumber-6					Punjab Kheera-1					
	0 day	**3 day**	**6 day**	**9 day**	**12 day**	**0 day**	**3 day**	**6 day**	**9 day**	**12 day**	**Mean storage**	**0 day**	**3 day**	**6 day**	**9 day**	**12 day**	**0 day**	**3 day**	**6 day**	**9 day**	**12 day**	**Mean storage**
NAA @ 25 ppm	0.00	4.38	16.70	34.15	58.42	0.00	4.47	17.02	34.40	58.83	**22.84**	0.00	4.96	17.91	33.82	59.59	0.00	5.04	18.09	34.04	60.05	**23.35**
NAA @ 50 ppm	0.00	4.38	16.59	34.01	58.28	0.00	4.46	16.90	34.30	58.71	22.76	0.00	4.93	17.75	33.66	59.42	0.00	5.02	17.97	33.95	59.95	23.26
GA3 @ 10 ppm	0.00	4.44	16.93	34.39	58.77	0.00	4.58	17.26	34.68	59.20	23.02	0.00	5.02	18.05	34.01	59.89	0.00	5.13	18.27	34.29	60.38	23.50
GA3 @ 20 ppm	0.00	4.41	16.80	34.24	58.58	0.00	4.55	17.13	34.56	59.00	22.93	0.00	4.98	17.94	33.90	59.71	0.00	5.08	18.17	34.19	60.17	23.41
Ethrel @ 100 ppm	0.00	4.49	17.06	34.54	58.92	0.00	4.63	17.37	34.79	59.34	23.12	0.00	5.09	18.25	34.20	60.09	0.00	5.16	18.30	34.34	60.47	23.59
Ethrel @ 200 ppm	0.00	4.50	17.12	34.65	59.04	0.00	4.67	17.48	34.89	59.46	23.18	0.00	5.09	18.33	34.35	60.23	0.00	5.18	18.39	34.44	60.60	23.66
Ethrel @ 100 ppm + GA3 @ 10 ppm	0.00	4.29	16.38	33.77	57.98	0.00	4.39	16.73	34.11	58.47	22.61	0.00	4.89	17.67	33.52	59.29	0.00	4.93	17.80	33.77	59.70	23.16
NAA @ 20 ppm + GA3 @ 10 ppm	0.00	4.23	16.12	33.47	57.65	0.00	4.34	16.42	33.78	58.07	22.41	0.00	4.79	17.41	33.22	58.95	0.00	4.87	17.59	33.51	59.35	22.97
NAA @ 25 ppm + ethrel @ 100 ppm	0.00	4.24	16.26	33.63	57.81	0.00	4.38	16.55	33.94	58.29	22.51	0.00	4.83	17.48	33.30	59.13	0.00	4.88	17.61	33.60	59.49	23.03
Control (water spray)	0.00	4.56	17.29	34.80	59.22	0.00	4.73	17.69	35.12	59.72	23.31	0.00	5.19	18.44	34.50	60.44	0.00	5.27	18.58	34.67	60.85	23.79
Mean varieties x storage	0.00	4.39	16.73	34.16	58.47	0.00	4.52	17.05	34.46	58.91		0.00	4.98	17.92	33.85	59.67	0.00	5.06	18.08	34.08	60.10	
Mean storage	0.00		4.46		16.89	34.31			58.69			0.00		5.02		18.00	33.96			59.89		
Mean varieties	22.75					22.99						23.28					23.46					
Factors	CD at 5%		SE (m)			Factors	CD at 5%		SE (m)			Factors	CD at 5%	SE (m)			Factors	CD at 5%	SE (m)			
Varieties	0.12		0.04			storage	0.20		0.07			Varieties	0.11	0.04			storage	0.18	0.06			
PGRs	0.26		0.10			Varieties x PGRs	NS		0.10			PGRs	0.25	0.09			Varieties x PGRs	NS	0.09			
Varieties x PGRs	NS		0.14			Storage x PGRs	NS		0.22			Varieties x PGRs	NS	0.13			Storage x PGRs	NS	0.20			
Varieties x PGRs x storage	NS		0.31									Varieties x PGRs x storage	NS	0.28								

Discussion

The findings align with previous studies indicating that postharvest weight loss is a complex phenomenon driven by respiration, transpiration and tissue degradation processes (Wills *et al*., 2007 [38]; Kader, 2002) [16]. In both years (2022-23 and 2023-24), the variety PPC-6 consistently recorded lower physiological loss in weight, decay loss and total loss values compared to PK-1 which showed higher PLW, respectively. The relatively better postharvest performance of PPC-6 may be attributed to its thicker cuticle and lower transpiration rates, which reduce water loss during storage. Similar varietal differences in storability were reported by Pal *et al*. (2018) [22], where 'KUK 9' outperformed 'Sevenstar' in terms of reduced weight loss, electrolyte leakage and decay percentage. Additionally, Sánchez *et al*. (2012) suggested that genotypic differences in cell wall integrity and respiration can significantly affect shelf life among cucumbers.

The lowest mean PLW was recorded in fruits treated with NAA @ 20 ppm + GA_3 @ 10 ppm, followed by NAA @ 25 ppm + ethrel @ 100 ppm. The highest PLW was observed in the control. The beneficial effect of GA_3 and NAA in minimizing PLW may be attributed to their role in delaying senescence, maintaining cell turgor and reducing ethylene biosynthesis, which slows down respiration and transpiration (Arteca, 1996 [5]; Dinesh *et al*., 2019) [11]. GA_3 application at 250 ppm was also found by Dinesh *et al*. to minimize postharvest weight loss and decay in cucumber cv. Malini under shade net conditions, supporting the present findings. Conversely, treatments with ethrel alone or in higher combinations tend to promote ethylene production and hasten fruit softening and deterioration (Watkins, 2006) [37], explaining the relatively higher PLW in those cases.

The maximum PLW, decay loss and total loss was recorded at 12 days in 2023-24. This trend aligns with Christodoulou *et al*. (2024) [10], who reported a steady decline in moisture, firmness and color over a 28-day cucumber storage trial, with visible textural degradation by day 13. Similarly, Sahel *et al*. (2024) [28] found that unpackaged cucumbers stored at ambient conditions lasted only 6 days due to high perishability, while modified atmosphere packaging (MAP) extended storage to 18 days by reducing moisture and gas exchange. These findings emphasize the importance of cold storage or MAP technologies in maintaining cucumber quality beyond 6-9 days.

Conclusion

Across both years and spacing systems, postharvest losses were influenced primarily by variety, plant growth regulators (PGRs) and storage duration. PPC-6 consistently exhibited the lowest losses at wider spacing, while PK-1 showed the highest losses at closer spacing. Among PGR treatments, NAA + GA_3 was most effective in minimizing losses, especially under wider spacing, whereas the control treatments led to the highest losses under closer spacing. Storage time had the most significant effect on losses, with minimal losses initially and a sharp increase by day 12. Both physiological loss in weight (PLW) and decay loss followed similar trends, increasing progressively with storage time. Total postharvest losses were lowest at the start and peaked by day 12 in both years, with slightly higher losses observed at closer spacing. Overall, while spacing, variety, and treatment played roles, storage duration had the most substantial impact on postharvest losses.

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