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Regression modelling of postharvest quality parameters of bitter gourd (*Momordica charantia* L.) under different packaging methods

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Abstract
Bitter gourd (*Momordica charantia* L.), a highly perishable Cucurbitaceae vegetable, undergoes rapid quality deterioration after harvest. The current study evaluated the effects of packaging methods such as low-density polyethylene (T_1), cling film (T_2), shrink wrap (T_3), and no packaging (T_4), under ambient (S_1) and cold storage (S_2) conditions using a factorial completely randomised design. Observations on physiological loss in weight (PLW), firmness, colour, spoilage, and shelf life were recorded over ten days. ANOVA revealed significant effects ($p<0.05$) of packaging, storage, and their interaction on all parameters. Shrink wrapping with cold storage (T_3S_2) was most effective, minimising PLW, maintaining firmness, reducing spoilage, and extending shelf life, followed by cling film under cold storage (T_2S_2). Regression modelling showed strong predictive accuracy with high R^2 values, confirming the robustness of the results. Overall, shrink wrapping in cold storage is recommended to optimise postharvest quality, enhance shelf life, and promote sustainable food security practices.

Keywords: Postharvest, quality, shelf life, packaging, shrink wrap, storage

1. Introduction

Bitter gourd (*Momordica charantia* L.), a member of the Cucurbitaceae family, grows well in tropical, subtropical, and temperate regions. However, it is highly perishable, with quality deterioration characterised by enlargement of the seed, softening of the flesh, yellowing of the outer skin, and a loss of its distinctive bitterness. Renowned for its exceptional nutritional profile, bitter gourd is an important ingredient in Vietnamese cuisine. It also holds significant value in traditional medicine, offering a wide range of therapeutic benefits for human health. Consequently, it has garnered increasing research attention in recent years. It is rich in essential nutrients, including carbohydrates, proteins, antioxidants, vitamin C, and vitamin A. Its health-promoting properties are largely attributed to its high antioxidant content, particularly ascorbic acid and β-carotene, which help neutralise free radicals. The characteristic bitterness of the fruit is attributed to the presence of the alkaloid compound momordicine. In addition to its nutritional benefits, it also possesses pharmacological properties. Numerous studies have highlighted its antidiabetic potential, primarily due to its hypoglycaemic activity (Han *et al.*, 2015) [7]. Despite these benefits, bitter gourd suffers from high postharvest losses and a short shelf life of only 4-5 days under ambient conditions (Salas and Pole, 2015) [24]. These losses not only reduce its market value but also negatively impact food security and farmers' income.

In bitter gourd, farm-level losses were estimated at 3.68% from physical damage, 2.1% due to physiological deterioration, and 6.68% as a result of biotic factors. Altogether, these factors contributed to a total postharvest loss of approximately 12.46% at the farm stage. At the trader level, physiological losses alone accounted for nearly 45 % of total losses, resulting in an overall loss of 21.88 % for bitter gourd (Kalpana *et al*. 2023) [10]. Postharvest losses are particularly high due to its highly perishable nature. The fruit's high moisture content, thin cuticle, and large surface area-to-volume ratio make it especially vulnerable to moisture loss and physical damage. Under tropical conditions, it undergoes rapid senescence, visible as yellowing, softening, and colour changes features that significantly reduce its marketability, as it is usually consumed in its firm, green stage. Microbial spoilage further contributes to the decline in quality. Although cold storage can help slow down these changes, its use is often limited due to the risk of chilling injury, a common issue in tropical crops.

Research has shown that individually wrapping fruits and vegetables in polymeric films can be an effective strategy to reduce spoilage, delay ripening, minimise chilling injury, and extend shelf life (Mohammed and Wickham, 1993) [15]. In the case of bitter gourd, such packaging approaches may help preserve postharvest quality by reducing moisture loss, slowing senescence, and preventing microbial decay.

Packaging plays a vital role in extending the shelf life and maintaining the quality of perishable produce by modifying the surrounding environment and reducing physiological deterioration. Among various packaging strategies, methods such as shrink wrapping, cling film wrapping, and LDPE packaging are gaining attention due to their ability to reduce weight loss, maintain firmness, and delay spoilage without chemical preservatives. The shelf life of fresh-cut produce is generally limited under ambient conditions, but it can be extended through various preservation approaches such as cold storage, controlled atmosphere, and other advanced packaging technologies.

Regression modelling serves as a powerful statistical tool to analyse and predict the relationship between packaging methods (independent variables) and postharvest quality parameters such as physiological weight loss, firmness, colour, and spoilage index (dependent variables). This approach aims to quantify the effectiveness of each packaging method and identify the most suitable one for maintaining bitter gourd quality during storage. By applying regression analysis, it becomes possible to understand how changes in packaging influence the rate of quality degradation over time. It helps in determining which packaging variables significantly affect postharvest performance and to what extent. This method also supports the development of predictive equations, allowing for the estimation of quality outcomes under varying conditions. The statistical outputs, such as R^2 values and p-values, further validate the reliability of the models. Regression modelling thus enables evidence-based comparisons among treatments. It reduces reliance on trial-and-error approaches by providing a scientific basis for packaging selection. Additionally, it facilitates optimisation of storage practices to minimise losses and enhance shelf life.

The current study aims to apply regression models to evaluate the effect of different packaging techniques on the postharvest quality parameters of bitter gourd. It further seeks to analyse the storage behaviour of bitter gourd under ambient conditions. Ultimately, the goal is to identify the most effective packaging system that can extend shelf life and improve marketability, thereby providing a scientific basis for reducing postharvest losses.

2. Materials and methods

2.1. Sample Collection

Freshly harvested, uniform, and disease-free bitter gourd (*Momordica charantia* L.) fruits were sourced from a local farm/market in Periyakulam. Medium-sized fruits at a similar stage of physiological maturity were carefully selected to ensure consistency and minimise experimental variability. The selected fruits were visually inspected to eliminate any with physical damage or blemishes. They were then carefully handled and transported to the postharvest laboratory in ventilated containers to maintain freshness and avoid mechanical injury during transit.

2.2. Experimental Design

The experiment was conducted at the Department of Postharvest Technology, Horticultural College and Research Institute, Periyakulam, to study the effect of different packaging methods and storage conditions on the postharvest quality of whole bitter gourd (*Momordica charantia* L.). A Factorial Completely Randomised Design (FCRD) with two factors was employed. The first factor was packaging method, which included four levels:

- **T_1** - Low-Density Polyethylene (LDPE) packaging
- **T_2** - Cling film wrapping
- **T_3** - Shrink wrapping
- **T_4** - Control (unpacked)

The second factor was storage condition, with two levels:

- **S_1** - Ambient storage
- **S_2** - Cold storage

Each treatment combination was replicated three times, resulting in a total of 24 experimental units. Random allocation of treatments was followed to reduce experimental bias and ensure valid statistical interpretation. Postharvest quality attributes were assessed to determine the effectiveness of packaging under different storage environments.

2.3. Packaging and Storage

Freshly harvested, uniform, and disease-free whole bitter gourd fruits were subjected to four packaging treatments to evaluate their effects on postharvest quality attributes. The treatments were given in table 1.

Table 1: Packaging treatment details

Treatment number	Packaging Treatment	Packaging Material
T_1	Low-density polyethylene packaging	LDPE
T_2	Cling film wrapping	Polyolefin
T_3	Shrink wrapping	HDPE
T_4	Control	Unpacked

In T_1, fruits were loosely packed in 100-gauge LDPE bags, allowing limited air exchange while offering a protective barrier against moisture loss. For T_2, individual fruits were wrapped with food-grade polyolefin cling film, which provides moderate permeability to gases and moisture, simulating retail-level packaging. In T_3, fruits were enclosed in HDPE shrink film and sealed using a shrink-wrapping machine equipped with a heat tunnel. The controlled heat application caused the film to shrink uniformly around the fruit, forming a tight and tamper-evident package. The T_4 group, which consisted of unpackaged fruits, served as the control. All packaging operations were carried out under hygienic conditions to simulate commercial postharvest handling standards and reduce contamination risk.

Each treatment group of whole bitter gourd fruits was packaged according to the assigned packaging method and stored under two different storage conditions, designated as S_1 and S_2.

Table 2: Storage treatment details

Treatment number	Storage Condition	Temperature (°C)	Relative Humidity (%)
S_1	Ambient storage	25±2	65-70
S_2	Cold storage	10±1	85-90

For the ambient condition, fruits were maintained at room temperature (25 ± 2°C) with a relative humidity of 65-70%. In the cold storage condition, samples were stored at 10 ± 1°C with 85-90% relative humidity. The storage period extended for 8 to 10 days, during which quality parameters were monitored. Observations were recorded at regular intervals of every 2 days (i.e., days 0, 2, 4, 6, 8, and 10), enabling the assessment of progressive changes under each treatment. The evaluation was carried out simultaneously for all packaging types across both storage conditions to facilitate comparative analysis.

2.4. Quality Parameters

The postharvest quality of whole bitter gourd fruits was evaluated at regular intervals during storage.

2.4.1. Physiological Loss in Weight (PLW%)

PLW was determined by measuring the difference between the initial and final weight of the bitter gourd fruits at each observation point. The weight loss was expressed as a percentage of the initial weight. It primarily results from moisture loss through transpiration and respiration and is a key indicator of freshness and marketability.

For the assessment of physiological weight loss in bitter gourd, fruits from each replication within every treatment were individually weighed using a digital electronic balance on days 2, 4, 6, 8 and 10 of storage. The percentage of weight loss was determined at each interval using the following formula, as described by Hassan (1998) [8]:

$$\text{PLW (\%)} = \frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \times 100$$

2.4.2. Firmness (kg/cm²)

Fruit firmness was measured using a penetrometer, and the results were expressed in kg/cm². Firmness reflects the textural quality of the fruit and its resistance to mechanical damage. A gradual decline in firmness is usually associated with softening due to enzymatic reactions such as the breakdown of cell wall components by pectinases and cellulases during ripening and senescence. Ekman *et al.* (2014) [6] reported that fruit softening was one of the major quality losses during postharvest storage of bitter gourd, occurring alongside yellowing and shrivelling, and was notably accelerated at higher storage temperatures of 21-25 °C compared to 7-10 °C.

2.4.3. Colour Change

Visual assessment of external colour was used to monitor changes during storage. Colour is a critical quality attribute that influences consumer acceptance. Progressive yellowing or loss of green pigmentation in bitter gourd was recorded as an indication of ripening and senescence. Colour changes in bitter gourd were evaluated using a numerical rating scale ranging from 0 to 5, where 0 represented fully green fruits, 1 indicated the breaker stage, 2 corresponded to up to 25% light yellowing, 3 denoted 26-50% yellow colouration, 4 indicated 51-75% yellowing, and 5 represented 76-100% yellowing. Similar scales were used by Jahan *et al.* (2020) [9].

Table 3: Visual colour rating scale for bitter gourd

Score	Description
0	Fully green
1	Breaker stage
2	Up to 25% light yellow
3	26-50% yellow
4	51-75% yellow
5	76-100% yellow

2.4.4. Spoilage Index (%)

Bhattacharjee and Dhua (2017) [1] reported that the spoilage index was calculated to evaluate the degree of microbial decay or visible rot in bitter gourd fruits during storage. The spoilage index was calculated to assess the extent of microbial decay or visible rotting in bitter gourd fruits during storage. At each observation interval, fruits showing signs of spoilage such as soft rot, fungal growth, discolouration, or off-odours were counted, and the index was expressed as the percentage of spoilt fruits relative to the total number of fruits in each treatment and replication. This parameter reflects the effectiveness of packaging and storage conditions in minimising postharvest losses due to biotic stress.

$$\text{Spoilage index (\%)} = \frac{\text{Number of spoiled fruits}}{\text{Total number of fruits}} \times 100$$

2.4.5. Shelf Life (days)

Shelf life was defined as the number of days the fruits remained marketable, based on visual quality, absence of spoilage, acceptable firmness, and colour. The endpoint was reached when fruits were deemed unfit for sale or consumption due to excessive deterioration. The shelf life of bitter gourd fruits was determined by monitoring disease severity daily on the same fruits from each replication. It was considered to have ended when the fruits exhibited minimal or no commercial value, following the approach described by Rashid *et al.* (2015) [22].

2.5. Statistical Analysis: The collected data were statistically analysed to evaluate the influence of packaging methods and storage duration on postharvest quality parameters of whole bitter gourd. A Factorial Completely Randomised Design (FCRD) was employed, with four packaging treatments (T_1-T_4) and two storage conditions (S_1-S_2), replicated thrice. Data were subjected to analysis of variance (ANOVA) to test for significant differences among treatments, storage types, and their interaction effects using R programming software (RStudio). Mean separation was carried out using the Least Significant Difference (LSD) test at a 5% significance level ($p<0.05$).

In addition to ANOVA, regression modelling was performed to establish quantitative relationships between the dependent variables (physiological weight loss, firmness, colour score, spoilage index, shelf life) and the independent variables (storage days, packaging treatments). Diagnostic plots and residual analysis were also conducted to ensure model assumptions (normality, homoscedasticity, independence) were not violated. Regression equations that showed significant fit ($p<0.05$) and high R^2 values were interpreted to understand the rate of change in quality attributes under various treatment combinations.

3. Results and Discussion

3.1. Physiological Weight Loss (%)

Shrink wrapping under cold storage (T_3S_2) recorded the minimum PLW (6.7%), while unpackaged fruits under ambient storage (T_4S_1) showed the highest loss (29%). Storage duration linearly increased PLW in all treatments, although packaging type and storage condition significantly affected the rate. During the 10th day, the highest PLW was found to be in unpackaged fruits, stored at ambient temperature (29%) and the lowest in shrink-wrapped fruits under cold storage (6.7%). The shrink wrapping (T_3) in general had lower weight loss compared to other treatments, followed by cling film (T_2) and LDPE (T_1). The weight loss was significantly decelerated in cold storage (S_2) in comparison to ambient storage (S_1). The lower fruit PLW in shrink-wrapped fruit might result from the tight film barrier, which decreases water and gas permeability. Shrink wrapping (T_3) was the most effective treatment in terms of average weight loss followed by cling film (T_2) and LDPE (T_1). Similar results were recorded for bitter gourd by Mohammed and Wickham (1993) [15] and for pointed gourd by Sahoo *et al.* (2015) [23]. This effect was primarily intensified by cold storage, as metabolism was reduced and thus, moisture loss was retarded.

Table 4: Effect of packaging methods and storage conditions on physiological weight loss (%) of bitter gourd

Treatments	PLW (%)				
	Day 2	Day 4	Day 6	Day 8	Day 10
T_1S_1: LDPE+Ambient storage	2.4	5.5	9.3	13.2	17.1
T_1S_2: LDPE+Cold storage	1.3	3.1	6	8.7	11
T_2S_1: Cling film+Ambient storage	1.8	4.2	7.6	10.9	14.3
T_2S_2: Cling film+Cold storage	1	2.5	5	7	9.5
T_3S_1: Shrink wrap+Ambient storage	1.2	2.8	5.5	7.8	9.8
T_3S_2: Shrink wrap+Cold storage	0.7	1.8	3.5	5	6.7
T_4S_1: Control+Ambient storage	4	9	16	23	29
T_4S_2: Control+Cold storage	2	4.5	8.2	11.4	14

3.2. Firmness (kg/cm²)

Fruit firmness steadily decreased during storage across all treatments. Shrink wrapping under cold storage (T_3S_2) maintained maximum firmness (4.15 kg/cm²), followed by cling film under cold storage (T_2S_2, 3.58 kg/cm²). The lowest firmness was in unpackaged fruits under cold storage (T_4S_2, 2.92 kg/cm²). The initial firmness of 6.20 kg/cm² dropped to 2.92 kg/cm² in unpackaged fruits kept under cold storage by the 10th day. In contrast, shrink-wrapped fruits maintained greater firmness at 4.15 kg/cm² under the same conditions. Overall, shrink wrapping and cling film proved to be the most effective packaging methods for preserving firmness, while unpackaged fruits softened much more quickly. Softening in bitter gourd is mainly linked to the enzymatic breakdown of pectin and cell wall polysaccharides (Ekman *et al.*, 2014) [6]. T_3S_2 was most effective in delaying softening due to its semi-permeable barrier combined with slowed metabolic activity under refrigeration. Packaging helped slow this process by reducing both water loss and mechanical stress. Shrink wrapping acted as a semi-permeable barrier, which helped maintain tissue firmness. Similarly, cold storage reduced enzymatic activity, aligning with the findings of Prajapati *et al.* (2021) [18].

Table 5: Effect of packaging methods and storage conditions on the firmness (kg/cm²) of bitter gourd

Treatments	Firmness (kg/cm²)				
	Day 2	Day 4	Day 6	Day 8	Day 10
T_1S_1: LDPE+Ambient storage	5.79	5.39	4.98	4.57	4.16
T_1S_2: LDPE+Cold storage	5.62	5.04	4.45	3.87	3.31
T_2S_1: Cling film+Ambient storage	5.93	5.67	5.4	5.12	4.83
T_2S_2: Cling film+Cold storage	5.88	5.55	5.23	4.9	3.58
T_3S_1: Shrink wrap+Ambient storage	6.07	5.85	5.62	5.4	5.97
T_3S_2: Shrink wrap+Cold storage	5.8	5.41	5.03	4.64	4.15
T_4S_1: Control+Ambient storage	5.6	5	4.4	4	3.6
T_4S_2: Control+Cold storage	5.36	4.52	3.68	3.3	2.92

3.3. Colour Change

The colour score gradually increased during storage, indicating progressive yellowing. Shrink wrapping under cold storage (T_3S_2) delayed yellowing most effectively (colour score 2.3), whereas unpackaged fruits under ambient storage (T_4S_1) exhibited maximum yellowing (score 5.0). By the 10th day, unpackaged fruits stored at ambient conditions showed the highest yellowing (score 5.0), while shrink-wrapped fruits under cold storage recorded the lowest score (2.3). Among the treatments, shrink wrapping (T_3) was most effective in delaying colour changes, followed by cling film (T_2). The better retention of green colour in shrink-wrapped fruits may be attributed to lower oxygen availability, which slows chlorophyll breakdown. Similar findings were reported by Lin *et al.* (2020) [12], who noted that packaging combined with low-temperature storage delays senescence and pigment loss in bitter gourd. These results highlight the synergistic effect of modified atmosphere and cold storage in maintaining visual quality.

Table 6: Effect of packaging methods and storage conditions on the colour change of bitter gourd

Treatments	Colour change				
	Day 2	Day 4	Day 6	Day 8	Day 10
T_1S_1: LDPE+Ambient storage	1	2	2.5	3	3.5
T_1S_2: LDPE+Cold storage	0.5	1	1.5	2	2.5
T_2S_1: Cling film+Ambient storage	1	2	2.8	3.5	4
T_2S_2: Cling film+Cold storage	0.5	1	1.5	2.3	3
T_3S_1: Shrink wrap+Ambient storage	0.8	1.5	2	2.6	3.2
T_3S_2: Shrink wrap+Cold storage	0.3	0.8	1.2	1.7	2.3
T_4S_1: Control+Ambient storage	1.2	2.6	3.5	4.3	5
T_4S_2: Control+Cold storage	0.8	1.8	2.5	3.5	4.3

3.4. Spoilage index (%)

The lowest spoilage incidence (6.7%) was observed in shrink-wrapped fruits under cold storage (T_3S_2), while the highest (76.7%) was recorded in unpackaged fruits under ambient storage (T_4S_1). The percentage of spoilage rose sharply with longer storage, with the highest levels recorded in unpackaged fruits (76.7% under ambient conditions by day 10). In contrast, shrink-wrapped fruits stored under cold conditions showed the lowest spoilage (6.7%). Among the packaging methods, shrink wrapping (T_3) provided the greatest protection against microbial decay, followed by LDPE (T_1). Packaging works by creating a physical barrier that limits microbial invasion, and shrink wrapping was particularly effective due to its tight, uniform seal. Similar results were observed by Bhattacharjee & Dhua (2017) [1], who found reduced microbial spoilage in coated bitter gourd fruits. Cold storage further suppressed microbial growth, in line with the findings of Zong *et al.* (1995) [30].

Table 7: Effect of packaging methods and storage conditions on the spoilage index (%) of bitter gourd

Treatments	Spoilage index (%)				
	Day 2	Day 4	Day 6	Day 8	Day 10
T_1S_1: LDPE+Ambient storage	0	6.7	13.3	20	30
T_1S_2: LDPE+Cold storage	0	3.3	6.7	10	13.3
T_2S_1: Cling film+Ambient storage	0	10	16.7	26.7	40
T_2S_2: Cling film+Cold storage	0	6.7	10	20	23.3
T_3S_1: Shrink wrap+Ambient storage	0	3.3	6.7	10	13.3
T_3S_2: Shrink wrap+Cold storage	0	0	3.3	3.3	6.7
T_4S_1: Control+Ambient storage	6.7	20	36.7	56.7	76.7
T_4S_2: Control+Cold storage	3.3	10	20	33.3	43.3

3.5. Shelf life

Shrink wrapping under cold storage (T_3S_2) extended the shelf life beyond 10 days, whereas unpackaged fruits under ambient storage (T_4S_1) lasted only 4 days. Shelf life differed significantly across treatments. Unpackaged fruits under ambient conditions had the shortest shelf life of just 4 days, while shrink-wrapped fruits stored under cold conditions lasted for more than 10 days. LDPE packaging extended shelf life to 8-9 days, and cling film maintained fruits for 6-10 days depending on storage conditions. The extended shelf life observed in shrink-wrapped fruits can be attributed to reduced water loss, slower softening, and lower spoilage levels. These results are consistent with the findings of Manivelu *et al.* (2017) [13], who identified shrink wrapping as an effective commercial technique for bitter gourd.

Table 8: Effect of packaging methods and storage conditions on the shelf life (days) of bitter gourd

Treatments	Shelf Life (days)
T_1S_1: LDPE+Ambient storage	8
T_1S_2: LDPE+Cold storage	9
T_2S_1: Cling film+Ambient storage	6
T_2S_2: Cling film+Cold storage	10
T_3S_1: Shrink wrap+Ambient storage	10
T_3S_2: Shrink wrap+Cold storage	>10
T_4S_1: Control+Ambient storage	4
T_4S_2: Control+Cold storage	6

3.6. ANOVA findings

The ANOVA results (Table 9-12) showed that packaging method, storage condition, and their interaction (T × S) had a significant effect on all quality parameters, including PLW, firmness, colour, spoilage index, and shelf life ($p < 0.05$). Critical difference (CD) values confirmed that shrink wrapping (T_3) was significantly different from the other packaging methods, especially when combined with cold storage (S_2). Storage condition also played a major role, with cold storage (S_2) consistently performing better than ambient storage (S_1) in preserving postharvest quality. The significance of both the main factors (packaging and storage) and their interaction indicates that fruit quality is influenced not just by the type of packaging but also by how it interacts with storage temperature. This underscores the need to choose the right packaging material together with the proper storage environment. On Day 2, firmness values across treatments (T_1-T_4) and storage conditions (S_1, S_2) remained very similar, ranging from about 5.6 to 6.0 kg/cm². The differences between treatments and storage were not large enough for the statistical test to show a significant interaction. This means that, at Day 2, the Treatment × Storage interaction effect on firmness was non-significant, indicating that variations among packaging and storage combinations had not yet become evident. However, from Day 4 onward, the interaction turned significant ($p<0.05$), showing that the combined effects of packaging and storage conditions on firmness became more pronounced with longer storage.

Table 9: Physiological Weight Loss (%) Initial weight = 175.00 g

Treatments	Day 2			Day 4			Day 6			Day 8			Day 10		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
T_1	2.4	1.3	1.85	5.5	3.1	4.3	9.3	6	7.65	13.2	8.7	10.95	17.1	11	14.05
T_2	1.8	1	1.4	4.2	2.5	3.35	7.6	5	6.3	10.9	7	8.95	14.3	9.5	11.9
T_3	1.2	0.7	0.95	2.8	1.8	2.3	5.5	3.5	4.5	7.8	5	6.4	9.8	6.7	8.25
T_4	4	2	3	9	4.5	6.75	16	8.2	12.1	23	11.4	17.2	29	14	21.5
Mean	2.35	1.25		5.375	2.975		9.6	5.675		13.725	8.025		17.55	10.3	

Factors	Day 2		Day 4		Day 6		Day 8		Day 10	
	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)
Treatment	0.033	0.071*	0.06	0.128*	0.131	0.28**	0.145	0.311**	0.215	0.459**
Storage	0.023	0.05*	0.042	0.042*	0.093	0.198*	0.103	0.22**	0.152	0.325**
T X S	0.047	0.1*	0.085	0.085*	0.185	0.396**	0.205	0.439**	0.304	0.65**

T_1 - Low-Density Polyethylene (LDPE) packaging
T_2 - Cling film wrapping
T_3 - Shrink wrapping
S_1 - Ambient storage
S_2 - Cold storage
T_4 - Control (unpacked)

Table 10: Firmness (kg/cm²) Initial firmness = 6.20 kg/cm²

Treatments	Day 2			Day 4			Day 6			Day 8			Day 10		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
T_1	5.79	5.62	5.705	5.39	5.04	5.215	4.98	4.45	4.715	4.57	3.87	4.22	4.16	3.31	3.735
T_2	5.93	5.88	5.905	5.67	5.55	5.61	5.4	5.23	5.315	5.12	4.9	5.01	4.83	3.58	4.205
T_3	6.07	5.8	5.935	5.85	5.41	5.63	5.62	5.03	5.325	5.4	4.64	5.02	5.97	4.15	5.06
T_4	5.6	5.36	5.48	5	4.52	4.76	4.4	3.68	4.04	4	3.3	3.65	3.6	2.92	3.26
Mean	5.8475	5.665		5.4775	5.13		5.1	4.5975		4.7725	4.1775		4.64	3.49	

Factors	Day 2		Day 4		Day 6		Day 8		Day 10	
	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)
Treatment	0.095	0.202**	0.085	0.181**	0.079	0.168**	0.068	0.144**	0.054	0.115**
Storage	0.067	0.143**	0.06	0.06*	0.056	0.119**	0.048	0.102**	0.038	0.081**
T X S	0.134	N/A	0.12	0.12*	0.111	0.238*	0.096	0.204*	0.076	0.163*

T_1 - Low-Density Polyethylene (LDPE) packaging
T_2 - Cling film wrapping
T_3 - Shrink wrapping
S_1 - Ambient storage
S_2 - Cold storage
T_4 - Control (unpacked)

Table 11: Colour Change Initial colour scale = 0.0

Treatments	Day 2			Day 4			Day 6			Day 8			Day 10		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
T_1	1	0.5	0.75	2	1	1.5	2.5	1.5	2	3	2	2.5	3.5	2.5	3
T_2	1	0.5	0.75	2	1	1.5	2.8	1.5	2.15	3.5	2.3	2.9	4	3	3.5
T_3	0.8	0.3	0.55	1.5	0.8	1.15	2	1.2	1.6	2.6	1.7	2.15	3.2	2.3	2.75
T_4	1.2	0.8	1	2.6	1.8	2.2	3.5	2.5	3	4.3	3.5	3.9	5	4.3	4.65
Mean	1	0.525		2.025	1.15		2.7	1.675		3.35	2.375		3.925	3.025	

Factors	Day 2		Day 4		Day 6		Day 8		Day 10	
	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)
Treatment	0.01	0.022**	0.024	0.052**	0.038	0.082**	0.054	0.116**	0.05	0.106**
Storage	0.007	0.016**	0.017	0.036**	0.027	0.058**	0.038	0.082**	0.035	0.075**
T X S	0.015	0.032*	0.034	0.073*	0.054	0.116*	0.077	0.165*	0.07	0.15*

T_1 - Low-Density Polyethylene (LDPE) packaging
T_2 - Cling film wrapping
T_3 - Shrink wrapping
S_1 - Ambient storage
S_2 - Cold storage
T_4 - Control (unpacked)

Table 12: Spoilage index (%) Initial spoilage index = 0.0

Treatments	Day 2			Day 4			Day 6			Day 8			Day 10		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
T_1	0	0	0	6.7	3.3	5	13.3	6.7	10	20	10	15	30	13.3	21.65
T_2	0	0	0	10	6.7	8.35	16.7	10	13.35	26.7	20	23.35	40	23.3	31.65
T_3	0	0	0	3.3	0	1.65	6.7	3.3	5	10	3.3	6.65	13.3	6.7	10
T_4	6.7	3.3	5	20	10	15	36.7	20	28.35	56.7	33.3	45	76.7	43.3	60
Mean	1.675	0.825		10	5		18.35	10		28.35	16.65		40	21.65	

Factors	Day 2		Day 4		Day 6		Day 8		Day 10	
	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)	SE (d)	C.D (p=0.05)
Treatment	0.048	0.103**	0.163	0.349**	0.185	0.395**	0.426	0.911**	0.712	1.522**
Storage	0.034	0.034*	0.115	0.247**	0.131	0.28**	0.301	0.644**	0.503	1.076**
T X S	0.068	0.068*	0.231	0.493*	0.261	0.559*	0.602	1.288*	1.007	2.152**

T_1 - Low-Density Polyethylene (LDPE) packaging
T_2 - Cling film wrapping
T_3 - Shrink wrapping
S_1 - Ambient storage
S_2 - Cold storage
T_4 - Control (unpacked)

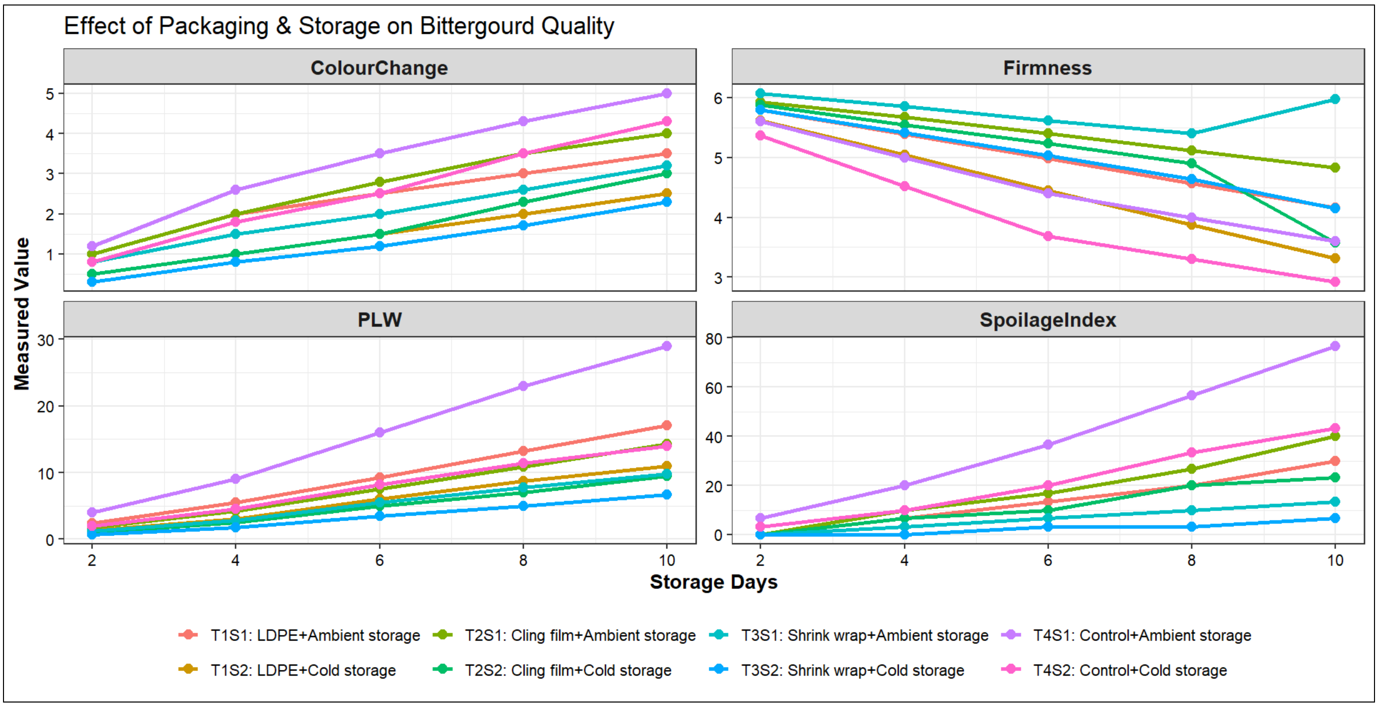

Fig 1: Effect of Packaging and Storage on Bitter Gourd Quality

Figure 1. Illustrates how PLW, firmness, colour change, and spoilage index evolved over the storage period under different packaging and storage conditions. The findings indicate that physiological deterioration progressed with time in all treatments, though at varying rates. Among the combinations, shrink wrapping under cold storage (T3S2) was the most effective. It consistently reduced PLW, preserved firmness, slowed down colour change, and minimised spoilage. In contrast, the control under ambient storage (T4S1) showed the fastest decline in quality, highlighting the crucial role of both proper packaging and low-temperature storage in extending freshness.

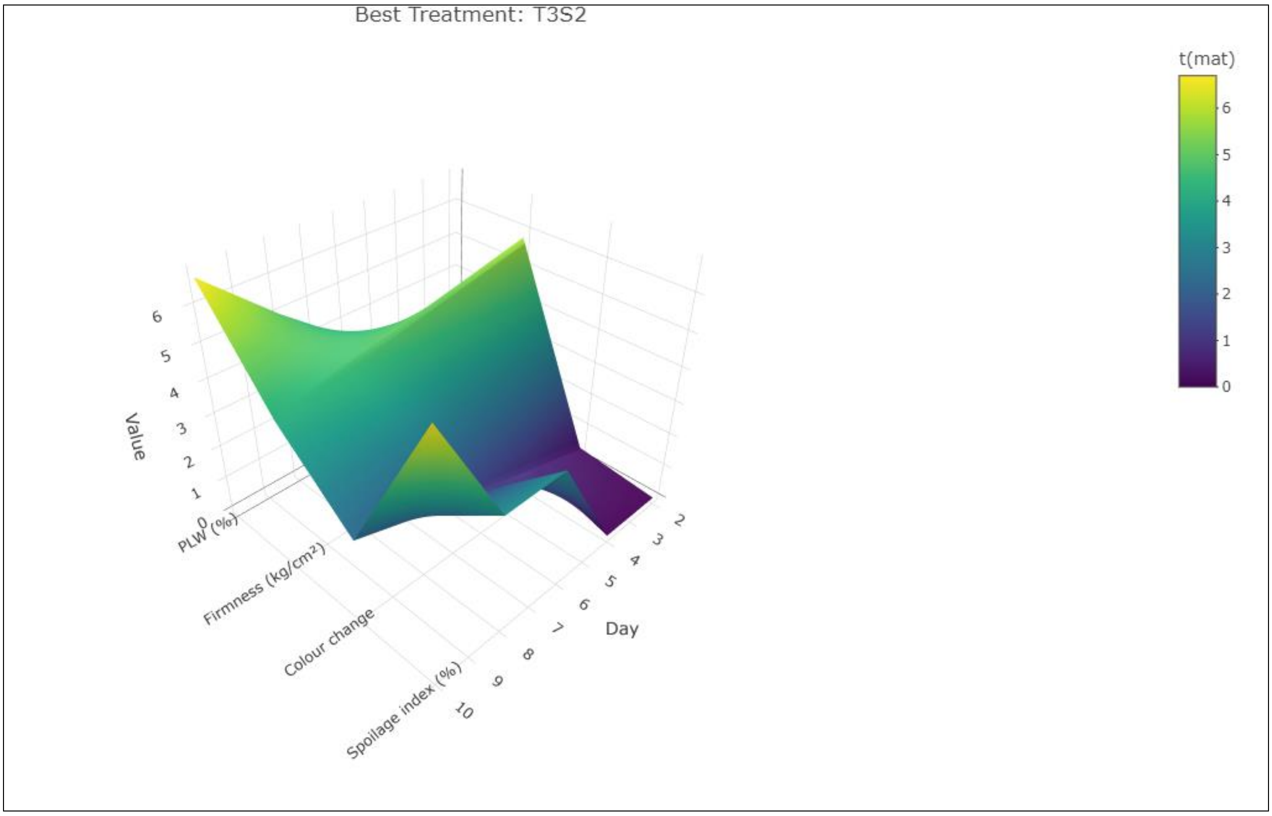

Fig 2: 3D Surface Plot Showing Postharvest Quality Parameters of Bitter Gourd under the Best Treatment (T_3S_2)

Fig 3: Contour Plot Showing Shelf Life of Bitter Gourd under Different Packaging and Storage Conditions

The 3D surface plot (Figure 2) visualises how postharvest quality parameters of bitter gourd changed over storage duration under the most effective treatment, T3S2 (shrink wrap + cold storage). The smooth gradient in the surface illustrates gradual changes in PLW, firmness, and colour during storage, with minimal fluctuations compared to other treatments. This confirms that T3S2 provided a stable modified atmosphere and reduced physiological stress, thereby preserving fruit quality for a longer period.

The contour plot (Figure 3) highlights the combined effect of packaging and storage on shelf life. Treatments involving cold storage consistently mapped to zones of extended shelf life, with shrink wrapping (T3S2) achieving the maximum preservation. In contrast, ambient-stored controls (T4S1) occupied the shortest shelf-life zones. The contour gradients illustrate how packaging methods interact with temperature to influence deterioration, reinforcing the finding that shrink wrapping under cold storage is the most effective strategy.

3.7. Regression analysis

The regression analysis showed that the model provided a strong fit when examining the effects of storage duration, packaging method, and postharvest quality parameters of bitter gourd. The Q-Q plot confirmed that the residuals were approximately normally distributed. Meanwhile, the residuals-versus-fitted values plot indicated no significant non-linearity, meaning the assumptions of linearity and independence were reasonably met. The regression model is appropriate because the relationship appears linear and the errors behave independently, with no strong pattern left unexplained. Cook's distance is a diagnostic statistic that measures how much a data point influences the regression model. Although a few data points (specifically those from data points 7, 15, and 31) deviated slightly from the overall pattern, they did not have a major impact on the model, as Cook's distance values stayed below the critical threshold. Some mild heteroscedasticity was observed, shown by a wider spread of residuals at higher fitted values, but this effect did not meaningfully reduce the reliability of the regression results. The Scale-Location plot suggested mild heteroscedasticity, as residual variance appeared to increase slightly with higher fitted values. However, the deviation was not severe, and the regression model remained robust for interpreting treatment and storage effects.

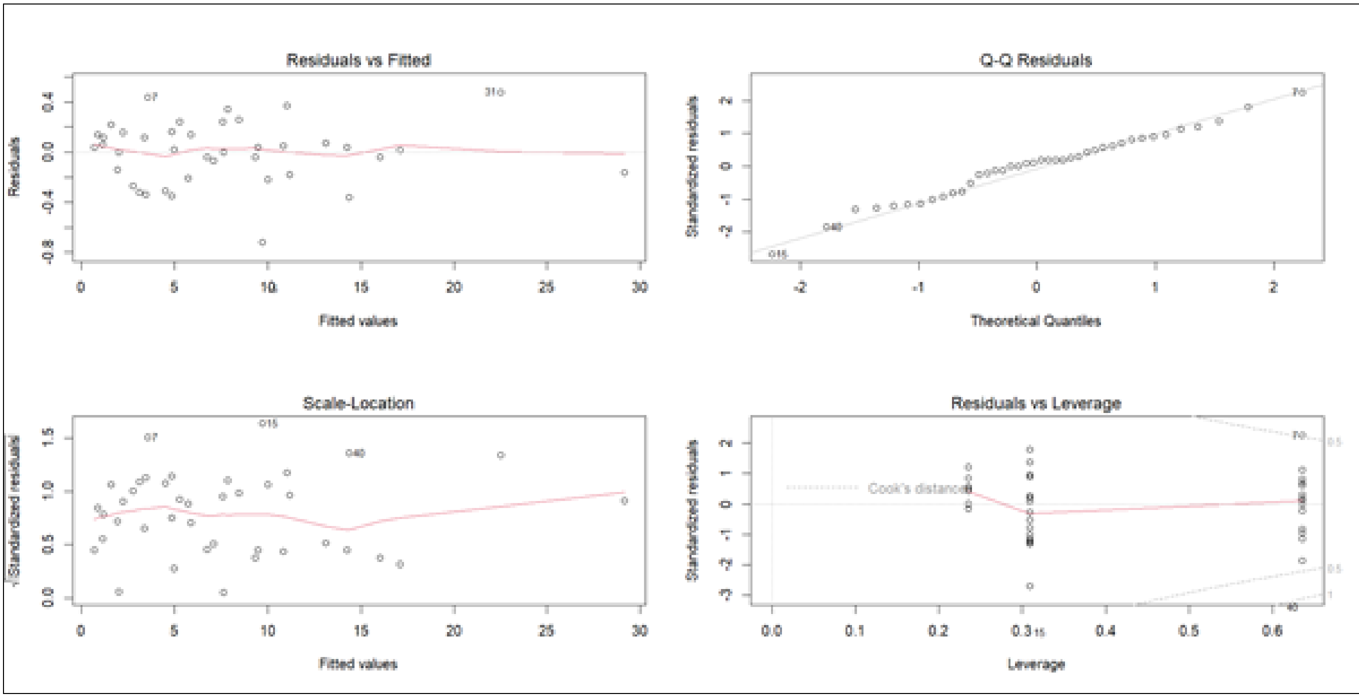

Fig 4: Diagnostic Plots of Regression Model for Quality Parameters of Bitter Gourd

These results show that regression modelling is a dependable method for predicting how bitter gourd behaves after harvest under different packaging and storage conditions. The close match between residuals and the theoretical distribution demonstrates the model's strength in tracking important quality changes, including weight loss, firmness, and spoilage. Although a small degree of heteroscedasticity was observed, it likely reflects natural biological variation and the interaction between packaging materials and storage conditions over time. Since no major influential outliers were detected, the predictive accuracy of the model is further supported. Overall, regression modelling not only confirms the statistical reliability of the treatment effects but also offers a practical way to estimate the shelf life of bitter gourd.

4. Conclusion

This study demonstrated that both the packaging method and storage conditions significantly influence the postharvest quality and shelf life of bitter gourd. Among the tested treatments, shrink wrapping under cold storage (T_3S_2) proved to be the most effective, as it consistently reduced weight loss, maintained firmness, minimised colour changes, and limited spoilage, followed by cling film wrapping under cold storage (T_2S_2) closely, also showing strong effectiveness in maintaining postharvest quality. As a result, this method extended the shelf life significantly compared to the other treatments. The regression modelling further reinforced these findings, demonstrating a strong model fit with high explanatory power across all quality parameters. The diagnostic plots also confirmed that key assumptions such as linearity, normality, and independence were met, with only minor heteroscedasticity observed, which did not affect the model's reliability.

In conclusion, combining factorial experiments with regression modelling provided a deeper understanding of how packaging and storage interact to affect bitter gourd quality. The findings highlight shrink wrapping with cold storage as the best strategy for preserving postharvest quality, reducing losses, and enhancing marketability. This research also highlights the importance of regression modelling as a predictive tool in postharvest studies, supporting the use of optimised packaging methods to enhance food security and sustainability.

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