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RESEARCH ARTICLE

Integrated organic nutrient management and modified atmosphere packaging improve postharvest quality and shelf life of okra (*Abelmoschus esculentus* L.)

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Abstract

Okra (*Abelmoschus esculentus* L.) is an important vegetable crop widely consumed for its nutritional and culinary value, yet it suffers from significant postharvest deterioration. This study investigated the combined effects of farmyard manure (FYM), organic modules and storage conditions on postharvest performance of okra fruits. The trials were conducted during 2021-22 and 2022-23 at the College of Horticulture, Rajendranagar, India. The experiment followed a factorial completely randomised design with 18 treatment combinations comprising three FYM levels (100 %, 75 % and 50 % of the recommended dose of nitrogen), three organic modules and two storage conditions: ambient storage and modified atmosphere packaging (MAP). Results demonstrated that higher FYM levels coupled with organic module 1 (Trichoderma viride enrichment, panchagavya and neem-based inputs) significantly improved fruit weight retention, minimised physiological loss in weight (PLW) and extended shelf life. Fruits from L_1M_1 stored under MAP recorded the longest shelf life (11.0 days) compared with less than 5.5 days in open storage. MAP effectively restricted PLW to below 3.5 % up to day 8, whereas open storage exceeded 20 % loss by day 4. Biochemical attributes, including total soluble solids, ascorbic acid and chlorophyll content, were also better preserved under MAP, particularly in fruits from 100 % FYM treatments. These results highlight the synergistic role of soil fertility management and protective packaging in maintaining okra quality. The adoption of integrated organic nutrient practices with MAP offers a practical strategy to reduce postharvest losses, improve nutritional retention and enhance the marketability of perishable vegetables.

Keywords: modified atmosphere packaging; organic nutrient management; postharvest quality; shelf life

Introduction

Okra (*Abelmoschus esculentus* L.), belonging to the family Malvaceae, is an annual herbaceous crop commonly known as lady's finger, bhindi and gumbo (1, 2). Native to Africa, okra is now extensively cultivated across tropical, subtropical and warm temperate regions of Asia, Southern Europe and the America (3). In India, okra is mainly cultivated during the rainy and summer seasons and ranks among the most important vegetable crops in terms of area and consumption. Cytogenetically, okra has a chromosome number of 2n = 130 and is a cross-pollinated species with outcrossing rates ranging from 11.8 % to 60 % (4). Okra is a highly valued crop due to its nutritional, culinary and industrial applications. Its immature green pods are consumed as a vegetable and used in soups, stews and sauces for their mucilaginous properties (5). Water-soluble polysaccharides derived from okra have applications in food processing industries, including ice creams, baked goods and chips, to enhance texture and stability (6). Fresh pods are rich in moisture (89.6 %), potassium, calcium, magnesium, phosphorus, vitamin C and trace minerals such as iron and aluminium (7). The dried fruits contain 13 %-22 % oil and 20 %-24 % protein, making them a potential source of edible oil and animal feed. Beyond its dietary role, okra offers several industrial and medicinal benefits. The stems and roots are traditionally used for clarifying sugarcane juice during jaggery preparation, while fibrous stems and mature pods are utilised in the paper industry (8). Medicinally, okra has been reported for its iodine content and its role in treating goitre, urinary disorders and chronic dysentery (9).

Despite its nutritional and industrial significance, okra is highly perishable and prone to postharvest deterioration. Physiological processes such as respiration, transpiration and ethylene production accelerate during storage, particularly under high-temperature conditions, leading to rapid senescence and quality decline (10, 11). Postharvest operations, including harvesting, handling and transportation, expose okra to mechanical damage and microbial infestation, further reducing its marketable quality (12, 13). In developing nations, postharvest losses of fresh vegetables, including okra, are estimated to range from 20 %-50 %, compared to 5 %-25 % in developed countries, with transportation delays alone contributing up to 20 % of total losses (14). To mitigate these losses, advanced packaging technologies such as MAP have been developed. MAP relies on polymeric films that regulate oxygen and carbon dioxide levels within the package, thereby reducing respiration, slowing enzymatic degradation and delaying senescence. The effectiveness of MAP depends on multiple factors, including product weight, storage temperature, film thickness, permeability and perforation density (15, 16). Polymeric films such as low-density polyethene (LDPE), polypropylene (PP) and biaxially oriented polypropylene (BOPP) are commonly employed in MAP due to their favourable gas permeability, durability and cost-effectiveness (17-19). These films maintain high CO_2 and low O_2 levels around the produce, thereby suppressing microbial activity, enzymatic browning and oxidative degradation while preserving nutritional quality and bioactive compounds (20, 21).

Okra, though highly valued for its nutritional and economic importance, is extremely perishable and undergoes rapid postharvest deterioration, resulting in significant quantitative and qualitative losses during storage and marketing. In developing countries, these losses often exceed 30 %-40 %, severely affecting farmer income and limiting consumer access to fresh produce. Conventional storage practices and reliance on chemical inputs are inadequate to maintain quality and safety, highlighting the need for alternative strategies. Integrating organic nutrient management with modern postharvest technologies such as MAP offers a sustainable and practical solution. MAP minimises physiological losses, preserves nutritional attributes and extends shelf life by creating a favourable microenvironment during storage. Importantly, the adoption of MAP supports Sustainable Development Goal (SDG) 12 on responsible consumption and production by reducing food waste, enhancing food safety and ensuring prolonged availability of fresh, minimally processed vegetables. Thus, innovations in nutrient management and packaging represent a viable pathway to address the dual challenges of postharvest losses and rising consumer demand for nutritious produce.

Materials and Methods

Experimental site and design

The study was carried out during the cropping seasons of 2021-22 and 2022-23 at administrative office, Sri Konda Laxman Telangana State Horticultural University, Mulugu, Siddipet comes under sub-tropical zone and is situated at a latitude of 17°43’02” N and a longitude of 78°37’34” E and altitude of 595 m above MSL, soil of the experimental site was sandy loam in texture and levelled. The experiment was conducted using a Factorial completely randomised design (FCRD) with two factors. Factor one included nine field treatments derived from a previous experiment involving different combinations of farmyard manure levels and organic modules. Factor two included two storage and packaging conditions. In total, eighteen treatment combinations were evaluated with three replications.

Source of fruits

Okra fruits were harvested at commercial maturity stage, characterised by a pod length of 7-9 cm, tender texture and bright green colour, from the field experiment comprising nine treatments that combined farmyard manure with three organic modules. The fruits were then sorted for uniformity in size, shape and colour and defective fruits were excluded. The selected fruits were subjected to two different storage and packaging conditions for quality evaluation for 10 days.

Field treatments

Factor one consisted of three farmyard manure levels: L_1: FYM equivalent to 100 % RDN; L_2: FYM equivalent to 75 % RDN and L_3: FYM equivalent to 50 % RDN. Levels of farmyard manure (FYM) based on the recommended dose of nutrients (RDN). The recommended dose of fertilisers (RDF) for okra is 100:50:50 kg NPK per hectare. Based on this, the FYM requirement was calculated using nitrogen as the reference nutrient. Accordingly, the levels of FYM were applied.

Organic modules

The organic modules consisted of a combination of soil application, seed treatment and foliar sprays (Table 1).

Storage and packaging conditions

Factor two comprised two storage conditions S_1: Open storage at ambient temperature of 28 ± 2 °C in plastic bowls and S_2: MAP using perforated low-density polyethene (LDPE) film of 107 µm thickness with an area of 0.075 m^2. The MAP samples were sealed with an impulse sealing machine. Gas composition inside the packages was analysed using a PBI Dansensor Checkpoint II and water vapour permeability was assessed using a Labthink TSY-W3 tester.

Treatment combinations

The combination of three manure levels, three organic modules and two storage conditions resulted in eighteen treatments designated as T_1 to T_{18}. Each treatment was replicated three times (Table 2).

Observations recorded

Data were collected on postharvest quality parameters at alternate-day intervals for 10 days.

Table 1. Components of different organic modules applied to okra

Module	Soil application	Seed treatment	Foliar sprays (10-day intervals from flowering)
M_1	*Trichoderma viride* @ 5 kg/ha in FYM + Neem cake @ 250 kg/ha	*Trichoderma viride* @ 4 g/kg seed	Panchagavya 3 %, Neem oil 5 %, *Beauveria bassiana* @ 5 g/L, *Bacillus thuringiensis* @ 1 kg/ha
M_2	*Pseudomonas fluorescens* @ 5 kg/ha in FYM + Neem cake @ 250 kg/ha	*Bacillus macerans* @ 3 % w/w	Vermiwash 10 %, Neem seed kernel extract 5 %, *Metarhizium anisopliae* @ 5 g/L, NPV @ 250 LE/ha
M_3	Vesicular arbuscular mycorrhizae (VAM) @ 10 kg/ha in FYM + Neem cake @ 250 kg/ha	Beejamrit 10 %	Jeevamruth 10 %, Neemastra 5 %, *Lecanicillium lecanii* @ 5 g/L, mixture of *Trichoderma* + *Pseudomonas spp.* @ 5 g/L

Table 2. Treatment combinations

Treatment code	FYM level (RDN Basis)	Organic module	Storage
T_1	100 % RDN	Module I	S_1
T_2	100 % RDN	Module I	S_2
T_3	100 % RDN	Module II	S_1
T_4	100 % RDN	Module II	S_2
T_5	100 % RDN	Module III	S_1
T_6	100 % RDN	Module III	S_2
T_7	75 % RDN	Module I	S_1
T_8	75 % RDN	Module I	S_2
T_9	75 % RDN	Module II	S_1
T_{10}	75 % RDN	Module II	S_2
T_{11}	75 % RDN	Module III	S_1
T_{12}	75 % RDN	Module III	S_2
T_{13}	50 % RDN	Module I	S_1
T_{14}	50 % RDN	Module I	S_2
T_{15}	50 % RDN	Module II	S_1
T_{16}	50 % RDN	Module II	S_2
T_{17}	50 % RDN	Module III	S_1
T_{18}	50 % RDN	Module III	S_2

Average fruit weight

Known quantities of okra fruits were weighed using an electronic balance (Sartorius BSA 320 2S, d = 0.01 g) before storage. Subsequent weights were recorded at alternate-day intervals during storage.

Physiological loss in weight

The physiological loss in weight was calculated as the percentage reduction in fruit weight from the initial value using the following formula (Eqn. 1):

$$\text{PLW (\%)} = \frac{\text{Initial weight -final weight}}{\text{Initial weight}} \times 100 \qquad \text{(Eqn. 1)}$$

Shelf life

Shelf life was recorded as the number of days fruits remained in marketable condition. Assessment was based on appearance, physiological loss in weight and incidence of spoilage or rotting.

Total soluble solids

Total soluble solids were determined using a Hanna digital refractometer (Model H196801). Homogenised pulp prepared from four fresh okra fruits (seeds excluded) was used for the measurement. Results were expressed as °Brix corrected at 20 °C.

Ascorbic acid content

Ascorbic acid content was determined using the 2,6-dichlorophenol indophenol titration method (22). Samples were extracted in 3 % metaphosphoric acid and titrated to a pink endpoint. The results were expressed in mg per 100 g of fresh sample.

Chlorophyll content

Total chlorophyll content in fresh fruits was determined following the method of Arnon (23). The median part of 3 g of fruit tissue was homogenised with magnesium sulfate and 80 % acetone. The extract was measured spectrophotometrically at 645 nm and 663 nm and expressed as mg per 100 g of fresh weight. Data recorded at successive intervals were subjected to analysis of variance (ANOVA). Treatment means were compared using the Least Significant Difference (LSD) test at 5 % probability level ($p \leq 0.05$). Standard error of mean [SE(m)] and critical difference (CD at 5 % or LSD at 5 %) values are presented for main effects (A: FYM levels, B: Organic modules) and their interaction (A × B). Cases marked as non-significant (NS) indicate no statistically meaningful difference.

Results and Discussion

Fruit weight

On the second day after harvest, significant variation in fruit weight was observed among treatments, with L_1M_1 (13.66 g) and L_1M_3 (12.67 g) (Table 3) recording the highest values. Lower manure levels (L_3M_2, L_3M_3) showed markedly reduced weights, averaging 15 %-18 % lower than full FYM application (L_1 treatments). This highlights the importance of 100 % FYM application in combination with organic modules for early weight retention. MAP consistently outperformed open storage, reducing postharvest weight loss by 8 %-12 % across treatments. By the fourth day, a general decline in weight was evident; however, L_1M_1 (12.87 g) retained ~29 % more weight than the lowest-performing treatment (L_3M_2, 9.39 g), while L_1M_3 (11.92 g) retained ~21 % more weight, confirming the advantage of integrating higher manure levels with organic modules under MAP. Treatments with 75 % and 50 % FYM showed reduced retention capacity, indicating nutrient insufficiency. MAP continued to be effective in minimising respiration and moisture loss. By the sixth and eighth days, further reductions occurred, with spoilage preventing measurements in several treatments. L_1M_1 retained higher weights under both storage conditions, while lower FYM levels and open storage accelerated spoilage, leading to pod rejection by the eighth and tenth days. This highlights the combined benefit of higher nutrient supply and protective packaging in prolonging marketability. Pooled means revealed consistent weight retention under MAP, declining from 12.25 g on day two to 11.97 g on day six. By the tenth day, nearly all pods under open storage spoiled, whereas MAP samples maintained acceptable quality. Interaction effects of FYM and storage were statistically non-significant beyond day four, though both factors were significant in the early period. Overall, applying full FYM with organic modules and storing under MAP emerges as an effective strategy to reduce postharvest losses in okra.

The results revealed that fruits harvested from treatment L_1M_1 (FYM equivalent to 100 % RDN + organic module-1) exhibited the highest average fruit weight. This improvement can be attributed to enhanced nutrient availability, which supported vigorous physiological activity and ensured adequate accumulation of food reserves. These reserves facilitated efficient partitioning towards developing fruits, thereby contributing to increased fruit weight. Additionally, plant growth regulators such

Table 3. Effect of different levels of farm yard manure integrated with organic modules and different storage, packing conditions on average fruit weight of okra (pooled analysis)

	2nd day			4th day			6th day		8th day		10th day	
Treatments	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	S_1	S_2	S_1	S_2
L_1M_1	13.10	14.21	13.66	11.60	14.13	12.87	*	13.92	*	13.57	*	13.15
L_1M_2	11.26	12.39	11.82	9.96	12.30	11.13	*	12.12	*	11.80	*	*
L_1M_3	12.13	13.21	12.67	10.71	13.12	11.92	*	12.93	*	12.62	*	12.21
L_2M_1	11.38	12.50	11.94	10.02	12.41	11.22	*	12.23	*	11.90	*	*
L_2M_2	10.69	11.76	11.23	9.38	11.66	10.52	*	11.49	*	11.14	*	*
L_2M_3	11.12	12.30	11.71	9.77	12.21	10.99	*	12.03	*	11.69	*	*
L_3M_1	10.44	11.60	11.02	9.16	11.48	10.32	*	11.31	*	10.98	*	*
L_3M_2	9.54	10.63	10.08	8.25	10.53	9.39	*	10.35	*	*	*	*
L_3M_3	10.51	11.68	11.10	9.13	11.57	10.35	*	11.39	*	*	*	*
Mean	11.13	12.25		9.78	12.16		--	11.97	--	9.30	--	--
	A	B	A × S	A	B	A × S	A	B	A	B	A	B
SE (m)	0.06	0.03	0.09	0.06	0.02	0.08	--	--	--	--	--	--
LSD (5 %)	0.19	0.09	NS	0.17	0.08	NS	--	--	--	--	--	--

'*': Okra pods unavailable for observation as all are spoiled/rejected. L_1: Farm yard manure equivalent to 100 %; L_2: Farm yard manure equivalent to 75 % RDN; L_3: Farm yard manure equivalent to 50 % RDN; M_1: Organic Module-1; M_2: Organic Module- 2; M_3: Organic Module- 3; S_1: Open at room temperature; S_2: Modified atmosphere packaging (MAP); A: Different levels of FYM and organic modules; S: Storage and packing conditions.

as auxin and cytokinin-like substances present in panchagavya may have played a key role in stimulating cell division and elongation, which ultimately enhanced fruit development. The accumulated food reserves further aided in the synthesis of pectin compounds, crucial for maintaining cell wall integrity, thereby reducing weight loss during storage (24-26). In terms of storage conditions, the S_2 treatment (modified atmosphere packaging) recorded the maximum fruit weight retention. This effect can be explained by the packaging film, which minimised water vapour diffusion into the surrounding atmosphere and maintained higher relative humidity within the package. As a result, respiration and transpiration rates were reduced, thereby delaying physiological weight loss in okra fruits during storage. Conversely, fruits stored under ambient conditions without protective films exhibited greater weight loss. This was primarily due to the large vapour pressure gradient between the internal tissues of fruits and the surrounding environment, coupled with higher metabolic activity leading to accelerated respiration and transpiration (27).

Physiological weight loss

On the second day, PLW varied significantly across treatments, with fruits stored under open room conditions showing much higher losses than those under MAP. The highest loss was recorded in L_3M_1 under open storage (11.02 %), while the same treatment under MAP exhibited only 0.91 % (Table 4). Similarly, L_1M_1 with 100 % FYM recorded an 8.20 % loss under open storage. The pooled mean indicated that MAP restricted weight loss to 0.79 %, compared with 9.85 % in open storage, demonstrating its strong protective effect against early deterioration. By the fourth day, weight loss increased sharply in open storage, ranging from 18.74 % (L_1M_1) to 22.41 % (L_3M_2), whereas MAP maintained substantially lower losses of 1.11 %-2.01 %. Treatments with 100 % FYM consistently showed the lowest PLW, while 50 % FYM levels recorded the highest, reflecting the importance of adequate nutrient supply in maintaining fruit quality. By the sixth day, several open storage treatments exhibited complete spoilage, preventing further observations. In contrast, MAP-treated fruits

Table 4. Effect of different levels of farm yard manure integrated with organic modules and different storage, packing conditions on physiological loss in weight (%) of okra (pooled analysis)

	2nd day			4th day			6th day		8th day		10th day	
Treatments	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	S_1	S_2	S_1	S_2
L_1M_1	8.20	0.52	4.36	18.74	1.11	9.92	*	2.55	*	4.94	*	7.91
L_1M_2	9.36	0.66	5.01	19.80	1.34	10.57	*	2.78	*	5.31	*	*
L_1M_3	8.90	0.61	4.76	19.56	1.27	10.42	*	2.70	*	5.03	*	8.13
L_2M_1	9.70	0.68	5.19	20.48	1.42	10.95	*	2.88	*	5.47	*	*
L_2M_2	10.00	0.83	5.42	20.99	1.71	11.35	*	3.14	*	6.05	*	*
L_2M_3	9.93	0.79	5.36	20.62	1.57	11.09	*	3.02	*	5.71	*	*
L_3M_1	11.02	0.91	5.97	21.94	1.85	11.89	*	3.22	*	6.11	*	*
L_3M_2	10.94	1.11	6.03	22.41	2.01	12.21	*	3.65	*	*	*	*
L_3M_3	10.59	0.98	5.79	22.24	1.86	12.05	*	3.40	*	*	*	*
Mean	9.85	0.79		20.75	1.57	9.92	*	3.04	*	4.29	*	*
	A	S	A × S	A	S	A × S	--	--	--	--	--	--
SE (m)	0.056	0.027	0.080	0.140	0.066	0.198	--	--	--	--	--	--
LSD (5 %)	0.162	0.077	0.230	0.404	0.190	0.571	--	--	--	--	--	--

'*': Okra pods unavailable for observation as all are spoiled/rejected. L_1: Farm yard manure equivalent to 100 %; L_2: Farm yard manure equivalent to 75 % RDN; L_3: Farm yard manure equivalent to 50 % RDN; M_1: Organic Module-1; M_2: Organic Module- 2; M_3: Organic Module- 3; S_1: Open at room temperature; S_2: Modified atmosphere packaging (MAP); A: Different levels of FYM and organic modules; S: Storage and packing conditions.

showed only 2.55 %-3.65 % loss, indicating a substantial delay in deterioration. By the eighth day, nearly all open-stored fruits had spoiled, whereas MAP still maintained acceptable quality. On the tenth day, all fruits in open storage had decayed completely, while MAP-treated pods recorded 4.94 %-8.13 % loss, though spoilage. Statistical analysis confirmed significant effects of FYM levels, storage conditions and their interactions during early and mid-storage. The superiority of 100 % FYM combined with organic module one under MAP highlights the synergistic role of soil fertility management and packaging in minimising postharvest physiological losses in okra.

Fruits harvested from treatment L_1M_1 (FYM equivalent to 100 % RDN + organic module-1) exhibited the lowest PLW. The combined application of FYM (100 % RDN), *Trichoderma viride* @ 5 kg ha^{-1} enriched in FYM and foliar spraying of 3 % *panchagavya* likely enhanced nutrient availability and photosynthetic efficiency, resulting in greater accumulation of assimilates. These assimilates contributed to the synthesis of pectin compounds, which are essential for maintaining cell wall integrity and firmness, thereby reducing moisture loss during storage. Earlier research also reported that crops fertilised with organic manure exhibited lower weight loss compared to those treated with chemical fertilisers, possibly due to improved micronutrient availability (24). Micronutrients are critical for strengthening cellular structures in fruits, which in turn reduces physiological weight loss. Conversely, fruits grown with chemical fertilisers tend to accumulate more moisture, thereby exhibiting higher PLW during storage.

PLW was observed to increase progressively with storage duration. Fruits stored under ambient conditions without packaging (S_1) recorded the highest weight loss. This was primarily attributed to the large vapour pressure gradient between fruit tissues and the surrounding atmosphere, which enhanced moisture loss, coupled with intensified biochemical processes such as respiration and transpiration. In contrast, fruits stored in modified atmosphere packaging (S_2) showed comparatively lower PLW, which increased gradually from the 2nd to the 10th day of storage. This effect can be explained by the creation of a microenvironment inside the package, saturated with moisture and characterised by reduced water vapour transmission, thereby minimising transpiration and weight loss (27). Among the interactions, $L_1M_1S_2$ (FYM equivalent to 100 % RDN + organic module-1 + modified atmosphere packaging) recorded the least PLW. The synergistic effect of improved nutrient assimilation and pectin synthesis due to organic nutrient management, combined with reduced transpiration losses under modified atmosphere packaging, effectively minimised weight loss throughout the storage period. Research indicates that the effectiveness of organic nutrient sources and modified atmosphere packaging in reducing post-harvest weight loss in okra and other horticultural crops (28-30).

Shelf life of okra

During 2021-22, maximum duration was achieved in L_1M_1 under MAP with 11.20 days, compared to 5.50 days under open storage. The shortest shelf life was noted in L_3M_2 under open storage (4.20 days) (Table 5). A similar pattern was observed in 2022-23, where L_1M_1 with MAP sustained 10.80 days, while treatments with reduced FYM under open storage lasted less than 5 days. These results demonstrate that full FYM application enhanced the physiological resilience of pods, thereby delaying spoilage. Across both years, MAP consistently outperformed open storage. In pooled data, MAP treatments ranged from 5.87 days (L_3M_2) to 11.00 days (L_1M_1), whereas open storage ranged between 4.35 and 5.45 days. On average, MAP extended shelf life to 7.93 days, nearly double that of open storage (4.82 days), underscoring the vital role of packaging in postharvest management. FYM levels also significantly influenced shelf life, with the treatments receiving 100 % recommended dose integrated with organic modules maintained longer shelf life, with L_1M_1 recording the highest pooled mean (8.23 days), followed by L_1M_3 (7.25 days). In contrast, treatments with 50 % FYM, such as L_3M_2 (5.11 days) and L_3M_3 (5.36 days), performed poorly. Statistical analysis confirmed significant effects of FYM levels, organic modules and storage methods across years and pooled data. Interaction effects revealed that the advantage of higher FYM was most pronounced under MAP. Thus, full FYM with organic module one under MAP provided the greatest extension of shelf life in okra.

The maximum shelf life was recorded under $L_1M_1S_2$ (FYM equivalent to 100 % RDN + organic module 1 + modified atmosphere packaging). This improvement can be attributed to enhanced nutrient availability from the integrated organic

Table 5. Effect of different levels of farm yard manure integrated with organic modules and different storage, packing conditions on shelf life (days) of okra during 2021-22, 2022-23 and pooled data

Treatments	2021-2022			2022-23			Pooled data		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
L_1M_1	5.50	11.20	8.35	5.40	10.80	8.10	5.45	11.00	8.23
L_1M_2	5.08	9.00	7.04	5.14	8.70	6.92	5.11	8.85	6.98
L_1M_3	5.12	9.25	7.19	5.16	9.48	7.32	5.14	9.36	7.25
L_2M_1	5.00	8.12	6.56	5.00	8.08	6.54	5.00	8.10	6.55
L_2M_2	4.60	7.61	6.11	4.80	7.45	6.13	4.70	7.53	6.12
L_2M_3	4.70	7.77	6.24	4.70	7.93	6.32	4.70	7.85	6.28
L_3M_1	4.40	6.38	5.39	4.60	6.67	5.64	4.50	6.52	5.51
L_3M_2	4.20	5.84	5.02	4.48	5.91	5.21	4.35	5.87	5.11
L_3M_3	4.40	6.21	5.31	4.50	6.34	5.42	4.45	6.27	5.36
Mean	4.78	7.94		4.86	7.92		4.82	7.93	
	A	**S**	**A × S**	**A**	**S**	**A × S**	**A**	**S**	**AXS**
SE (m)	0.07	0.03	0.10	0.07	0.03	0.10	0.07	0.03	0.09
LSD (5 %)	0.21	0.10	0.30	0.21	0.10	0.30	0.19	0.09	0.26

'*': Okra pods unavailable for observation as all are spoiled/rejected. L_1: Farm yard manure equivalent to 100 %; L_2: Farm yard manure equivalent to 75 % RDN; L_3: Farm yard manure equivalent to 50 % RDN; M_1: Organic Module-1; M_2: Organic Module- 2; M_3: Organic Module- 3; S_1: Open at room temperature; S_2: Modified atmosphere packaging (MAP); A: Different levels of FYM and organic modules; S: Storage and packing conditions.

module, which promoted photosynthesis and facilitated the synthesis of sufficient assimilates. These assimilates supported the production of pectin compounds that strengthen cell wall integrity, thereby reducing tissue breakdown during storage. In addition, the use of MAP reduced chlorophyll degradation and minimised physiological loss in weight, collectively contributing to the extended shelf life of okra fruits. Research indicates that integrated nutrient management and MAP significantly improved storage stability (31, 32).

The effectiveness of MAP in extending shelf life has also been reported in several horticultural crops. Research indicates that MAP delayed ripening and reduced weight loss in tomato fruits without compromising physicochemical or sensory quality (33). Likewise, Research indicates ivy gourd fruits stored in non-perforated polyethene and polypropylene packages exhibited better moisture retention, lower physiological loss in weight and prolonged shelf life (34). Furthermore, Research indicates that baby spinach leaves stored under modified atmospheres (5 % O_2, 15 % CO_2, balance N_2) at 4 °C for nine days maintained higher antioxidant activity, retained flavonoid levels and showed increased shelf life (35). Research indicates that the combination of organic nutrient management with MAP provides a synergistic advantage by improving physiological resilience, reducing metabolic deterioration and maintaining postharvest quality, thereby substantially enhancing the shelf life of okra fruits.

Total soluble solids

The data on total soluble solids (TSS) presented in Table 6 showed significant differences among FYM levels, organic modules and storage conditions, while their interactions were non-significant. On the second day, TSS showed significant variation among treatments. The highest TSS was recorded in L_1M_1 (7.38 °Brix), followed by L_1M_3 (7.27 °Brix), while the lowest values were observed in L_3M_2 (6.09 °Brix) and L_3M_1 (6.36 °Brix). The pooled mean indicated slightly higher TSS under open storage (6.90 °Brix) compared to MAP at 6.72 °Brix, suggesting that dehydration in open conditions concentrated soluble solids. By the fourth day, TSS increased across treatments, with L_1M_1 maintaining the highest value (7.53 °Brix) and L_3M_2 the lowest (6.29 °Brix). Fruits under open storage consistently exhibited higher TSS than MAP, likely due to greater water loss, whereas MAP moderated solute concentration by preserving internal moisture. From the sixth day onward, spoilage restricted data availability, though L_1M_1 and L_1M_3 sustained relatively higher values, while 50 % FYM treatments showed lower TSS. MAP maintained greater stability, with smaller fluctuations compared to the sharp increases observed in open storage. By the tenth day, TSS could be recorded only in limited treatments, with L_1M_1 (7.44 ° Brix) and L_1M_3 (7.30 °Brix) retaining the highest levels. Treatments with reduced FYM (50 % RDN) exhibited complete spoilage by day 10. The pooled mean indicated a rise from 6.90 °Brix on day two to 7.16 °Brix on day four, with subsequent stabilisation under MAP. Statistical analysis confirmed significant effects of FYM levels and storage conditions in the early period, though interactions were non-significant. Overall, full FYM with organic module one under MAP consistently maintained higher TSS and reduced spoilage, highlighting its effectiveness for okra storage.

The mean values of TSS recorded on the 6th, 8th and 10th day of storage revealed a consistent increasing trend (Table 6). TSS represents the concentration of sugars and other soluble components such as carbohydrates, proteins, fats, minerals and organic acids and is considered an important index of ripening and overall eating quality (36). A higher TSS value reflects greater accumulation of soluble solids, which directly influences the flavour and consumer acceptability of fruits. The highest TSS during storage was observed under S_1 (open storage at room temperature). This increase can be attributed to the degradation of pectic substances and the hydrolysis of polysaccharides, particularly starch, into simpler sugars over time (37). The phenomenon is strongly associated with ripening-related metabolic changes, where complex carbohydrates are progressively broken down into monosaccharides and oligosaccharides, thereby increasing TSS content during storage. Among the nutrient management treatments, L_1M_1 (FYM equivalent to 100 % RDN + organic module-1) registered the highest TSS. The enhanced TSS values under this treatment may be attributed to the availability of nitrogen, which promotes higher biomass production and photosynthetic assimilate accumulation. These assimilates, in turn, contribute to increased sugar content in fruit tissues (25). Conversely, the lowest TSS values

Table 6. Effect of different levels of farm yard manure integrated with organic modules and different storage, packing conditions on TSS (°Brix) of okra of pooled analysis

	2nd day			4th day			6th day		8th day		10th day	
Treatments	S_1	S_2	**Mean**	S_1	S_2	**Mean**	S_1	S_2	S_1	S_2	S_1	S_2
L_1M_1	7.45	7.31	7.38	7.71	7.34	7.53	*	7.37	*	7.4	*	7.44
L_1M_2	7.26	7.06	7.16	7.47	7.12	7.29	*	7.13	*	7.15	*	*
L_1M_3	7.35	7.20	7.27	7.55	7.21	7.38	*	7.24	*	7.27	*	7.3
L_2M_1	7.12	6.96	7.04	7.39	7.02	7.21	*	7.07	*	7.11	*	*
L_2M_2	6.81	6.66	6.73	6.98	6.72	6.85	*	6.75	*	6.76	*	*
L_2M_3	6.93	6.8	6.87	7.22	6.84	7.03	*	6.88	*	6.9	*	*
L_3M_1	6.46	6.27	6.36	6.78	6.3	6.54	*	6.32	*	6.36	*	*
L_3M_2	6.21	5.98	6.09	6.54	6.05	6.29	*	6.08	*	*	*	*
L_3M_3	6.53	6.26	6.39	6.76	6.30	6.53	*	6.35	*	*	*	*
Mean	6.90	6.72		7.16	6.77		--	6.8	--	--	--	--
	A	**S**	**A × S**	**A**	**S**	**A × S**	--	--	--	--	--	--
SE (m)	0.05	0.02	0.07	0.04	0.02	0.06	--	--	--	--	--	--
LSD (5 %)	0.15	0.07	NS	0.13	0.06	NS	--	--	--	--	--	--

'*': Okra pods unavailable for observation as all are spoiled/rejected. L_1: Farm yard manure equivalent to 100 %; L_2: Farm yard manure equivalent to 75 % RDN; L_3: Farm yard manure equivalent to 50 % RDN; M_1: Organic Module-1; M_2: Organic Module- 2; M_3: Organic Module- 3; S_1: Open at room temperature; S_2: Modified atmosphere packaging (MAP); A: Different levels of FYM and organic modules; S: Storage and packing conditions.

during storage were observed in S_2 (modified atmosphere packaging). This could be explained by the altered gaseous composition inside the packaging, which reduced respiration and transpiration rates, consequently slowing down ripening. Since the accumulation of soluble solids is closely linked to starch metabolism, the inhibition of respiratory processes under modified atmospheres delays carbohydrate breakdown and sugar accumulation (38). Furthermore, the controlled microenvironment created within MAP prevents rapid utilisation of sugars as respiratory substrates, thereby limiting the rise in TSS compared to fruits stored in open conditions (39). The present findings corroborate earlier studies, with significant TSS variations reported in tomato under different storage conditions and similar trends observed in okra (40, 41). These results reinforce the role of both storage atmosphere and nutrient management in regulating postharvest changes in TSS.

Ascorbic acid content

Ascorbic acid levels varied significantly across treatments and storage conditions. MAP consistently preserved higher vitamin C compared to open storage, with pooled means of 13.24 mg/100 g under MAP versus 11.90 mg/100 g under open storage on the second day. The superiority of MAP was maintained throughout storage, where pooled means remained 12.92 mg/100 g under MAP and 10.40 mg/100 g under open storage by the fourth day. Pre-harvest nutrition played a crucial role, as treatments with 100 % FYM (L_1) recorded significantly higher ascorbic acid than reduced manure levels (L_2 and L_3). Among them, L_1M_1 under MAP consistently retained the maximum ascorbic acid across storage intervals. From the sixth day onward, spoilage eliminated open storage data, while MAP still maintained appreciable levels (>13 mg/100 g) until the tenth day, demonstrating its effectiveness in prolonging okra quality. Statistically, the effects of FYM levels and storage conditions were significant in the early storage period, whereas their interaction was non-significant. Practically, this confirms that a full FYM application combined with MAP is essential to sustain vitamin C and extend shelf life.

The results indicated significant differences in ascorbic acid content among the different levels of FYM and organic modules, with the maximum concentration observed in L_1M_1 (FYM equivalent to 100 % RDN + organic module 1) (Table 7). Since ascorbic acid is a carbohydrate derivative, any factor enhancing carbohydrate synthesis tends to increase its accumulation in fruits. The improved vegetative growth under this treatment likely facilitated efficient capture of solar energy in the presence of balanced nutrients, leading to higher carbohydrate production and metabolite accumulation. These metabolites subsequently contributed to elevated ascorbic acid levels in the fruit (41). A gradual decline in ascorbic acid content was observed across all treatments during storage. This reduction is expected, as ascorbic acid is water-soluble and highly susceptible to oxidation, often being converted into dehydroascorbic acid over time. In the present study, however, the highest ascorbic acid retention during storage was recorded in fruits stored under modified atmosphere packaging (S_2). This effect can be attributed to the packaging material, which maintained high relative humidity and reduced moisture loss, thereby lowering the respiration rate. The reduced respiration and slower ripening helped in preserving ascorbic acid content. In contrast, fruits stored under open conditions at room temperature (S_1) showed the lowest ascorbic acid content, likely due to accelerated oxidative degradation of L-ascorbic acid (38). Similar progressive declines in ascorbic acid content during storage have been reported (30, 41).

Significant interaction effects were also recorded, particularly on the 4th day of storage. The highest ascorbic acid content was noted in $L_1M_1S_2$ (FYM equivalent to 100 % RDN + organic module 1 + modified atmosphere packaging). The integration of organic nutrient management with FYM and Trichoderma viride @ 5 kg ha^{-1} enriched in FYM supported higher carbohydrate accumulation and metabolite synthesis. This, in turn, enhanced the ascorbic acid content at harvest, highlighting the positive role of combined organic inputs. Storing these fruits in MAP further preserved the ascorbic acid by reducing respiration and moisture loss through the maintenance of a humid microenvironment inside the package. The combined effect of enhanced nutrient-driven metabolite accumulation and MAP-induced reduction in oxidative degradation ensured higher ascorbic acid retention throughout the storage period (38).

Table 7. Effect of different levels of farm yard manure integrated with organic modules and different storage, packing conditions on the ascorbic acid of okra (pooled analysis)

	2nd day			4th day			6th day		8th day		10th day	
Treatments	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	S_1	S_2	S_1	S_2
L_1M_1	14.27	15.31	14.79	12.99	14.97	13.98	*	14.67	*	14.13	*	13.59
L_1M_2	13.13	14.19	13.66	11.79	13.92	12.85	*	13.49	*	13.03	*	*
L_1M_3	14.16	14.93	14.54	12.73	14.61	13.67	*	14.32	*	13.92	*	13.47
L_2M_1	11.76	13.49	12.62	10.18	13.21	11.69	*	12.92	*	12.26	*	*
L_2M_2	10.95	12.73	11.84	9.32	12.33	10.82	*	11.88	*	11.36	*	*
L_2M_3	11.77	13.07	12.42	10.33	12.68	11.51	*	12.22	*	11.78	*	*
L_3M_1	10.62	12.18	11.4	9.23	11.88	10.55	*	11.38	*	11	*	*
L_3M_2	9.93	11.39	10.66	8.18	11.11	9.65	*	10.69	*	*	*	*
L_3M_3	10.5	11.9	11.20	8.88	11.54	10.21	*	11	*	*	*	*
Mean	11.90	13.24		10.40	12.92		--	12.51	--	9.72	--	--
	A	**S**	**A × S**	**A**	**S**	**A × S**	--	--	--	--	--	--
SE (m)	0.10	0.04	0.14	0.10	0.04	0.14	--	--	--	--	--	--
LSD (5 %)	0.28	0.13	0.40	0.29	0.13	0.41	--	--	--	--	--	--

'*': Okra pods unavailable for observation as all are spoiled/rejected. L_1: Farm yard manure equivalent to 100 %; L_2: Farm yard manure equivalent to 75 % RDN; L_3: Farm yard manure equivalent to 50 % RDN; M_1: Organic Module-1; M_2: Organic Module- 2; M_3: Organic Module- 3; S_1: Open at room temperature; S_2: Modified atmosphere packaging (MAP); A: Different levels of FYM and organic modules; S: Storage and packing conditions.

Chlorophyll content

The effect of different levels of FYM along with organic modules and storage and packaging on chlorophyll (mg/100 g) content of okra was presented in Table 8, showing a significant difference among the treatments. Chlorophyll content decreased progressively with increasing storage duration. On the second day, chlorophyll content varied significantly across treatments, with the highest value in L_1M_1 under MAP at 1.12 mg/100 g, followed by L_1M_3 (1.07 mg/100 g). The lowest was observed in L_3M_2 under open storage (0.49 mg/100 g). The pooled mean indicated that MAP preserved higher chlorophyll content (0.84 mg/100 g) compared with open storage (0.74 mg/100 g), highlighting the role of packaging in delaying pigment loss, particularly under adequate nutrient management. By the fourth day, chlorophyll declined across all treatments, though MAP continued to maintain higher levels. L_1M_1 (1.09 mg/100 g) and L_1M_3 (1.05 mg/100 g) recorded the highest values, while L_3M_2 under open storage showed only 0.41 mg/100 g. The pooled means were 0.80 mg/100 g in MAP and 0.62 mg/100 g in open storage. Treatments receiving 100 % FYM consistently sustained higher pigment content, demonstrating the role of balanced nutrient input in delaying chlorophyll degradation. From the sixth day onward, spoilage-limited open storage observations leave MAP as the viable option. Under MAP, L_1M_1 and L_1M_3 retained 1.05 and 1.01 mg/100 g, respectively, while open storage treatments were spoiled. By the eighth and tenth days, MAP-treated pods still maintained relatively high values (1.01 and 0.99 mg/100 g in L_1M_1; 0.96 and 0.91 mg/100 g in L_1M_3), whereas lower FYM levels failed to sustain quality.

The pooled analysis confirmed a progressive decline in chlorophyll, but the reduction was slower under MAP. Statistical analysis showed significant effects of FYM levels, storage conditions and their interactions during the second and fourth days, with minimal error and LSD values indicating the superiority of L_1M_1 under MAP. Overall, integrating 100 % FYM with the organic module under MAP proved most effective in retaining chlorophyll, delaying senescence and extending the shelf life of okra. The results revealed that L_1M_1 (FYM equivalent to 100 % RDN + organic module-1) consistently recorded the maximum chlorophyll content during 2021-22, 2022-23 and in pooled data (Table 8). This improvement can be attributed to the combined application of FYM equivalent to 100 % RDN, *Trichoderma viride* at 5 kg ha^{-1} enriched in FYM and neem cake, along with foliar application of 3 % panchagavya. These practices enhanced nutrient mineralisation and mobilisation, ensuring greater availability of Fe, N, P and S to plants, which are crucial for chlorophyll biosynthesis. The application of organic fertilisers has been reported to positively influence chlorophyll accumulation (26). The increased chlorophyll concentration likely enhanced photosynthetic activity, resulting in higher assimilate production.

Chlorophyll retention is particularly important in okra since its bright green colour is a key determinant of marketability. In the present study, MAP (S2) played a crucial role in preserving chlorophyll content. The modified gaseous environment, characterised by reduced O_2 and elevated CO_2, delayed chlorophyll degradation and prevented yellowing of okra during storage. Conversely, fruits stored under ambient conditions without packaging (S_1) exhibited substantial chlorophyll loss and developed a pale appearance toward the end of storage, indicating advanced senescence. This degradation in non-climacteric vegetables such as okra has been attributed to the activity of chlorophyllase enzymes and is a common indicator of quality loss (42). Research indicates that declining chlorophyll levels occur during storage in okra and capsicum (27, 30). Similar results are observed in previous studies in sprouts and leafy vegetables (43).

The interaction between nutrient management and storage conditions was significant. The treatment $L_1M_1S_2$ (FYM equivalent to 100 % RDN + organic module-1 + modified atmosphere packaging) recorded the highest chlorophyll content during storage. Enhanced nutrient mobilisation and uptake under organic nutrient management facilitated higher chlorophyll biosynthesis at harvest. Furthermore, storing fruits under MAP reduced respiration rates, enhanced antioxidant activity and delayed chlorophyll degradation due to the synergistic effect of low O_2 and high CO_2 conditions. Research indicates that improved chlorophyll stability in fresh produce under MAP (44).

Table 8. Effect of different levels of farm yard manure integrated with organic modules and different storage, packing conditions on chlorophyll content of okra (pooled analysis)

Treatments	2nd day			4th day			6th day		8th day		10th day	
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	S_1	S_2	S_1	S_2
L_1M_1	1.00	1.12	1.06	0.87	1.09	0.98	*	1.05	*	1.01	*	0.99
L_1M_2	0.88	1.04	0.96	0.78	1.01	0.89	*	0.97	*	0.95	*	*
L_1M_3	0.95	1.07	1.01	0.81	1.05	0.93	*	1.01	*	0.96	*	0.91
L_2M_1	0.79	0.87	0.83	0.66	0.82	0.74	*	0.77	*	0.74	*	*
L_2M_2	0.68	0.73	0.7	0.55	0.68	0.62	*	0.65	*	0.62	*	*
L_2M_3	0.71	0.79	0.75	0.59	0.76	0.67	*	0.72	*	0.7	*	*
L_3M_1	0.59	0.69	0.64	0.43	0.65	0.54	*	0.63	*	0.61	*	*
L_3M_2	0.49	0.58	0.53	0.41	0.54	0.48	*	0.51	*	*	*	*
L_3M_3	0.54	0.65	0.60	0.44	0.62	0.53	*	0.58	*	*	*	*
Mean	0.74	0.84		0.62	0.80		--	0.76	--	0.62	--	--
	A	**S**	**A × S**	**A**	**S**	**A × S**	--	--	--	--	--	--
SE (m)	0.006	0.003	0.008	0.007	0.003	0.01	--	--	--	--	--	--
LSD (5 %)	0.017	0.008	0.024	0.02	0.009	0.028	--	--	--	--	--	--

'*': Okra pods unavailable for observation as all are spoiled/rejected. L_1: Farm yard manure equivalent to 100 %; L_2: Farm yard manure equivalent to 75 % RDN; L_3: Farm yard manure equivalent to 50 % RDN; M_1: Organic Module-1; M_2: Organic Module- 2; M_3: Organic Module- 3; S_1: Open at room temperature; S_2: Modified atmosphere packaging (MAP); A: Different levels of FYM and organic modules; S: Storage and packing conditions

Conclusion

The findings establish that integrating full FYM with organic nutrient modules significantly enhances the postharvest physiological and biochemical quality of okra fruits. Among the evaluated treatments, L_1M_1 (100 % FYM with organic module-1) consistently outperformed other combinations by supporting higher fruit weight retention, reduced physiological losses and improved stability of ascorbic acid and chlorophyll. When coupled with modified atmosphere packaging, these benefits were further amplified. MAP effectively slowed respiration and transpiration, maintained pigment concentration and restricted oxidative degradation, thereby extending shelf life by nearly twofold compared with ambient storage. The interaction between nutrient availability and controlled storage conditions proved crucial in preserving marketable quality. This dual strategy of preharvest organic management and postharvest packaging provides a sustainable solution to address the challenges of perishability in okra. By reducing food losses and enhancing nutritional security, the approach aligns with sustainable development priorities and offers a scalable model for vegetable supply chains in developing regions. Broader adoption could contribute to resilient horticultural production and improved consumer access to fresh, nutritious produce.

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Authors' contributions

RRT conducted the experiment and drafted the manuscript. AKK was responsible for planning the experiment and reviewing the manuscript. TSK conceptualized and designed the experiment, as well as edited and reviewed the manuscript. BNK coordinated and planned the overall work and participated in reviewing the manuscript. GS carried out the statistical analysis. All authors have read and approved the final version of the manuscript for publication.

Compliance with ethical standards

Conflict of interest: The Authors do not have any conflicts of interest to declare

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