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INFLUENCE OF MODIFIED ATMOSPHERIC PACKAGING ON PHYSIOLOGICAL AND BIOCHEMICAL SEED QUALITY OF CAPSICUM (*CAPSICUM ANNUUM*L.) SEEDSDURING STORAGE

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ABSTRACT

Seed longevity plays a pivotal role in ensuring sustainable crop productivity and quality seed supply. Modified atmospheric packaging (MAP) is a promising technology to preserve seed viability by altering the gaseous composition of nitrogen (N) oxygen (O) and carbon dioxide (CO_2). This study evaluated the effect of modified atmospheric packaging (MAP) using varying levels of N_2, O_2 and CO_2 along with vacuum, cold storage (10°C) and atmospheric air (control) on hybrid capsicum (*Capsicum annuum* L.) seeds storability. Results revealed that seeds stored under 40% N_2 + 0% O_2 + 60% CO_2 (T_{10}) retained superior seed quality attributes, recorded seed quality parameters*viz.*,thousand seed weight (4.63 g), germination percentage (90.33%), mean seedling length (13.08 cm), seedling dry weight (20.88 mg), seed vigour Index-I (1158) seed vigour index-II (1868) speed of germination (15.06), seed moisture content (5.80%) and least seed mycoflora (Nil). Among all treatments, T_{10} (40% N_2 + 00% O_2 + 60% CO_2) has showed as the most effective atmospheric combination for retaining physiological seed quality, closely followed by T_7 (60% N_2 + 00% O_2 + 40% CO_2). Vacuum packaging (T_1) and cold storage (T_2) also showed positive effects. This study concluded that low-oxygen and CO_2 -enriched environments significantly retard deterioration and ideal for long-term storage of hybrid *Capsicum* seeds.

***Key words*: Capsicum, Modified atmospheric packaging, Storage, Seed quality**

Introduction

Capsicum (*Capsicum annuum* L.), commonly known as bell pepper, is an economically important horticultural crop of the family Solanaceae, cultivated worldwide for fresh consumption and processing (Tripodi & Kumar, 2019). The crop is valued for its attractive fruit colours and high nutritional content, particularly vitamins A, C and E, dietary fibre and antioxidants (Howard *et al*., 2000; Soare *et al*., 2017). Bell pepper seeds are small and exhibit comparatively poor germination and shorter longevity, making seed quality and storage management critical for successful cultivation (Chen & Lott, 1992; Bissoli *et al*., 2022). Seed deterioration during storage is largely associated with oxidative stress caused by reactive oxygen species, leading to loss of viability and vigour under unfavourable storage conditions (Bordolui *et al*., 2015). Modified Atmosphere (MA) storage, achieved by reducing oxygen and increasing carbon dioxide or nitrogen levels, effectively suppresses respiration, insect activity and biochemical degradation, thereby extending seed longevity (Banks & Fields, 1995). Hence, Modified Atmospheric Packaging (MAP) offers an eco-friendly and residue-free approach for maintaining physiological seed quality of bell pepper during storage.An experiment was conducted with an objectiveis to study the influence of modified atmospheric packaging on physiological seed quality of bell pepper over a period of storage.

Plate 1: Overview of modified atmospheric packaging unit.

Material and Methods

The present investigation was undertaken at the All India Coordinated Research Project on Seed (Crops), National Seed Project, University of Agricultural Sciences (UAS), GKVK, Bengaluru, during August 2024 to June 2025. Packaging operations were carried out at ICAR–AICRP on Post-Harvest Engineering and Technology, UAS, GKVK, using a modified atmosphere packaging (MAP) unit (Plate. 1). The laboratory experiment was laid out in a Completely Randomized Design (CRD) with fifteen treatments replicated thrice. Treatments comprised different gaseous combinations of nitrogen (N_2), oxygen (O_2) and carbon dioxide (CO_2), along with vacuum packaging and cold storage. The treatments were as follows:

T_0 – Control (atmospheric gas)

T_1 – Vacuum package

T_2 – Cold storage at 10°C

T_3 – 100% N_2 + 0% O_2 + 0% CO_2

T_4 – 80% N_2 + 5% O_2 + 15% CO_2

T_5 – 70% N_2 + 10% O_2 + 20% CO_2

T_6 – 60% N_2 + 10% O_2 + 30% CO_2

T_7 – 60% N_2 + 0% O_2 + 40% CO_2

T_8 – 50% N_2 + 20% O_2 + 30% CO_2

T_9 – 40% N_2 + 10% O_2 + 50% CO_2

T_{10} – 40% N_2 + 0% O_2 + 60% CO_2

T_{11} – 30% N_2 + 10% O_2 + 60% CO_2

T_{12} – 20% N_2 + 10% O_2 + 70% CO_2

T_{13} – 15% N_2 + 5% O_2 + 80% CO_2 and

T_{14} – 0% N_2 + 0% O_2 + 100% CO_2

Plate 2: Overview of (a) vacuum, (b) atmospheric packed and (c) modified atmospheric packed seeds and stored under ambient conditions.

Freshly harvested seeds of the hybrid *Pasarella* (*Capsicum*), procured from Rijk Zwaan Seeds Pvt. Ltd., and were used for the study. Seeds (1000 per pouch) were packed in aluminium foil pouches under respective gaseous environments. Gas cylinders (N_2, O_2 and CO_2) were regulated at 7 kg cm^{-2} and mixed in a controlled chamber connected to a buffer tank. Prior to sealing, a vacuum was applied to expel residual air, followed by flushing with the desired gas mixture. Pouches were hermetically sealed and the internal gas composition was verified using a Checkmate gas analyzer to ensure accuracy. All sealed pouches were stored in cartons under ambient and cold conditions until analysis (Plate 2 and plate 3).

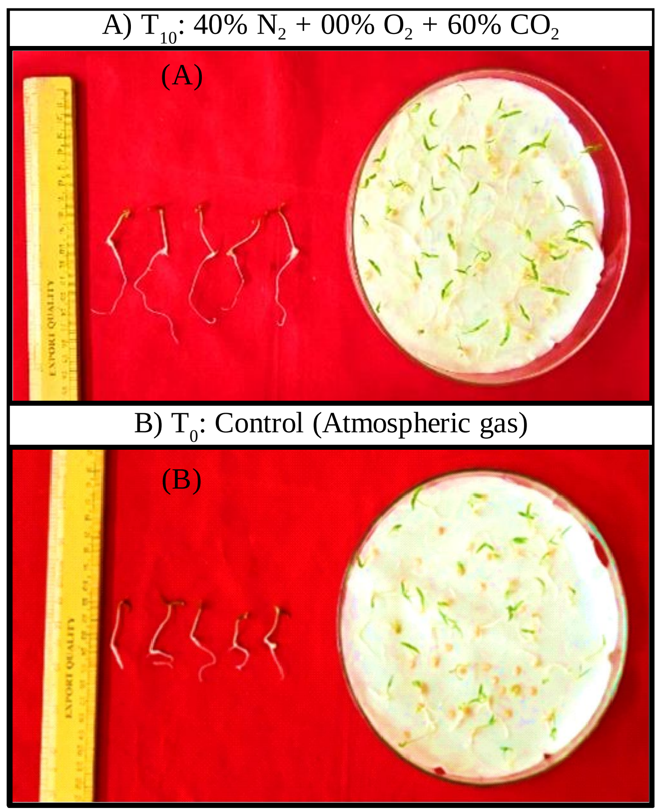

Plate 3: Germination and seedling length of capsicum seeds after ten months of modified atmospheric storage.

Table 1: Initial seed quality parameters of capsicum seeds.

Sr.	Seed quality parameters	Observations
1	1000 seed weight (g)	5.28
2	Moisture content (%)	5.50
3	Germination (%)	96.67
4	Mean seedling length (cm)	15.15
5	Seedling dryweight(mg/seedling)	23.14
6	Seedvigourindex-I	1464
7	Seedvigourindex–II	2236
8	Electricalconductivity ((dS/m/g of seed)/g of seed)	0.229
9	Dehydrogenaseactivity(A_{480nm})	0.910
10	Totalsolubleprotein(µg/g)	88.23
11	Catalase(mMolH_2O_2 decomposed/g/min)	4.06
12	Peroxidaseactivity($\Delta OD_{430}min^{-1}g^{-1}$)	667.43
13	Seedmycoflora (%)	Nil

The physical, physiological and biochemical seed quality parameters and were assessed initially and at bimonthly intervals up to ten months of storage period: August 2024 to June 2025. At each interval, 400 seeds per treatment were sampled. Germination (%) was tested following the between paper method (Anon., 2021) at 25 ± 1 °C and 90% RH, with first and final counts on the 5^{th} and 14^{th} day, respectively. Mean seedling length (cm) and mean seedling dry weight (mg) were recorded at final count and were used to calculate seed vigour index I and IIaccording to Abdul-Baki & Anderson (1973). Seed moisture content (%) was determined by the high constant temperature oven method (Anon., 2021)andThe electrical conductivity (EC) of seed leachate was measured from the steeped water of 25 soaked seeds in a digital conductivity meter (Model: Systronic conductivity meter 306) and expressed in dS/m/g of seed (Anon., 2021). The total dehydrogenase activity of the seeds is estimated as per the method described by Franca Neto *et al.*, (1998). Total soluble seed protein was estimated in the dry seed tissues as per Lowry *et al.*, (1951). Catalase activity was measured based on an assay of hydrogen peroxide on the formation of its stable complex with ammonium molybdate (Goth, 1991). The peroxidase activity was carried out according to Sadasivam & Manickam (2008). The data generated were subjected to statistical analysis using Analysis of Variance (ANOVA) appropriate for CRD, as outlined by Snedecor & Cochran (1967). A significance level of 5% ($P \leq 0.05$) was applied and treatment means were compared using the critical difference (CD) test wherever ANOVA indicated significance.

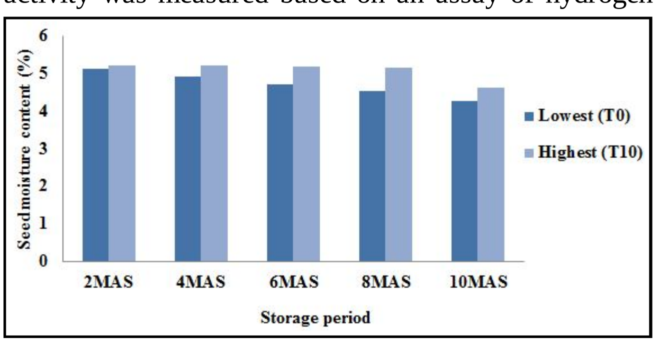

Fig. 1: Influence of modified atmospheric storage conditions on seed moisture content of capsicum seeds during storage.

Results and Discussion

Influence of different storage conditions on physical and physiological seed quality parameters

The seeds had an initial thousand seed weight of 5.28g, seed moisture content of 5.50%, germination percent about 96.67%, mean seedling length of 15.15cm, seedling dry weight of 23.14 mg, seedling vigour index-I about 1464, seedling vigour index-II about 2236, electrical conductivity of 0.229 dS/m/g of seed)/g of seed, dehydrogenase activity of 0.910 (A_{480nm}), total soluble protein of 88.23 µg/g, catalase activity of 4.06 mMol H_2O_2 decomposed/g/min and peroxidase activity of 667.43 at $\Delta OD_{430}min^{-1}g^{-1}$. The observations recorded on the seed parameters are presented (Table 1). The initial quality assessment of hybrid capsicum seeds revealed high physiologicalvigour, essential for long-term storage and market readiness. The high seedling vigour suggested efficient reserve mobilization and metabolic activity.

After ten months of storage, significant differences were observed in the physiological seed quality of capsicum among storage treatments (Supplementary data-Table 2, Table 3 and Table 4). Thousand seed weight declined across all treatments; however, the reduction was least under vacuum packaging (T_1: 4.66 g) and 40% N_2+ 60% CO_2 (T_{10}: 4.63 g), while atmospheric air (T_0) recorded the lowest value (4.27 g) (Fig. 1). The slower

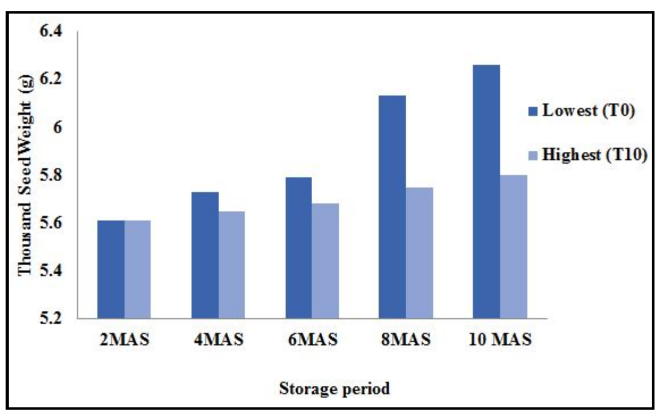

Fig. 2: Influence of modified atmospheric storage conditions on thousand seed weight (g) of capsicum seeds during storage.

Table 2: Influence of modified atmospheric storage conditions on thousand seed weight (g) of hybrid *Capsicum* seeds during storage (Supplementary data).

Treatments	Thousand seed weight (g)					Seed moisture content (%)				
	2MAS	4MAS	6MAS	8MAS	10MAS	2MAS	4MAS	6MAS	8MAS	10 MAS
T_0	5.14	4.91	4.70	4.55	4.27	5.61	5.73	5.79	6.13	6.26
T_1	5.27	5.25	5.20	5.11	4.66	5.50	5.62	5.63	5.68	5.73
T_2	5.14	5.20	4.81	4.73	4.57	5.53	5.67	5.67	5.87	6.02
T_3	5.19	5.08	4.81	4.65	4.63	5.66	5.68	5.72	5.83	5.85
T_4	5.13	5.05	4.82	4.50	4.38	5.70	5.67	5.73	5.81	5.89
T_5	5.16	5.01	4.91	4.54	4.43	5.70	5.71	5.85	5.89	5.91
T_6	5.14	5.14	4.91	4.56	4.37	5.66	5.69	5.76	5.79	5.92
T_7	5.16	5.19	5.09	5.16	4.63	5.57	5.65	5.70	5.78	5.82
T_8	5.14	4.90	4.78	4.43	4.35	5.68	5.72	5.76	5.94	6.18
T_9	5.16	4.83	4.83	4.59	4.33	5.63	5.74	5.83	5.86	6.09
T_{10}	5.23	5.22	5.18	5.16	4.63	5.61	5.65	5.68	5.75	5.80
T_{11}	5.17	5.09	4.73	4.62	4.38	5.69	5.69	5.71	5.91	5.93
T_{12}	5.03	5.02	4.86	4.56	4.31	5.61	5.66	5.68	6.03	6.14
T_{13}	5.17	4.80	4.80	4.61	4.41	5.69	5.71	5.73	5.96	6.20
T_{14}	5.13	5.02	4.82	4.76	4.54	5.64	5.68	5.72	6.07	6.10
Mean	**5.17**	**5.05**	**4.88**	**4.70**	**4.46**	**5.63**	**5.69**	**5.69**	**5.92**	**5.98**
S.Em±	**0.128**	**0.090**	**0.071**	**0.08**	**0.045**	**0.11**	**0.08**	**0.07**	**0.07**	**0.09**
CD(P=0.05)	**NS**	**0.257**	**0.203**	**0.229**	**0.128**	**NS**	**NS**	**NS**	**0.19**	**0.26**
CV	**4.290**	**3.577**	**2.919**	**3.426**	**2.017**	**3.66**	**2.56**	**2.39**	**2.35**	**3.55**

Note: MAS: Months after storage **NS:** Non-significant

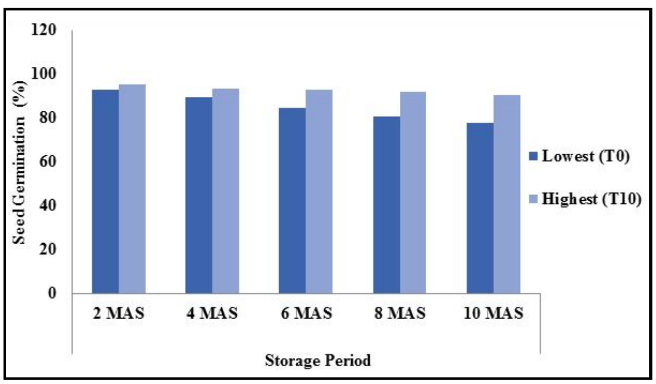

Fig. 3: Influence of modified atmospheric storage conditions on seed germination (%) of capsicum seeds during storage.

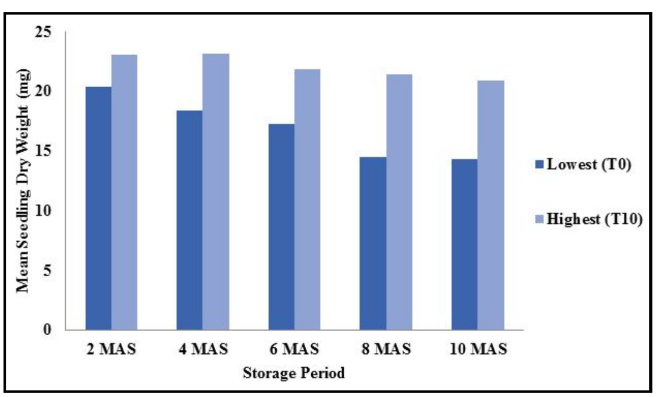

Fig. 4: Influence of modified atmospheric storage conditions on mean seedling length (cm) of capsicum seeds during storage.

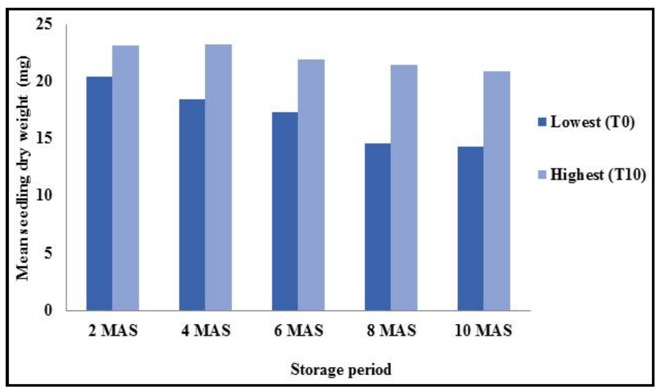

Fig. 5: Influence of modified atmospheric storage conditions on mean seedling dry weight (g) of capsicum seeds during storage.

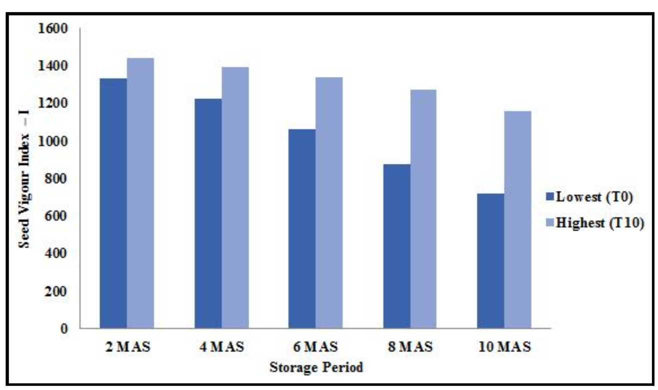

Fig. 6: Influence of modified atmospheric storage conditions on seed vigour index -I of capsicum seeds during storage.

Table 3: Influence of modified atmospheric storage conditions on seed germination (%), mean seedling length (cm) and mean seedling dry weight (mg) of capsicum seeds during storage (Supplementary data).

Treat-ments	Seed germination (%)					Mean seedling length (cm)					Mean seedling dry weight (mg)				
	2 MAS	4 MAS	6 MAS	8 MAS	10 MAS	2 MAS	4 MAS	6 MAS	8 MAS	10 MAS	2 MAS	4 MAS	6 MAS	8 MAS	10 MAS
T_0	92.67	89.33	84.33	80.67	77.67	14.23	13.53	12.12	10.79	9.24	20.37	18.41	17.29	14.54	14.34
T_1	95.24	93.67	91.67	90.00	88.33	14.91	14.39	14.16	13.42	11.97	23.02	23.02	21.24	20.22	20.06
T_2	95.33	93.33	91.00	88.67	85.67	14.73	14.22	13.76	12.64	11.41	22.99	22.23	20.70	19.76	19.17
T_3	93.33	92.67	90.67	88.00	87.67	14.57	14.06	13.41	12.06	11.27	22.49	21.84	21.06	19.48	18.59
T_4	93.67	91.40	90.00	87.67	85.67	14.39	13.98	12.99	12.31	10.84	21.76	20.61	19.66	18.25	17.01
T_5	94.00	92.33	89.33	86.67	86.67	14.67	14.03	13.33	12.05	10.64	21.68	20.10	19.86	18.38	17.63
T_6	94.67	91.00	90.00	87.67	87.67	14.47	13.93	13.13	11.99	10.51	22.08	20.26	19.95	18.77	17.48
T_7	95.00	92.67	92.00	91.67	89.33	14.93	14.48	14.14	13.54	12.40	23.04	23.15	21.34	20.91	20.31
T_8	93.67	90.67	84.67	88.33	83.00	14.28	13.90	12.52	11.41	11.39	20.65	19.66	19.09	16.80	16.85
T_9	95.00	92.33	90.00	86.33	87.33	14.47	14.06	13.43	11.81	10.24	21.89	21.48	19.88	18.07	17.71
T_{10}	95.33	93.33	92.67	92.00	90.33	14.95	14.64	14.37	13.80	13.08	23.11	23.20	21.89	21.46	20.88
T_{11}	93.67	90.67	88.33	86.67	86.33	14.57	14.08	13.12	12.09	10.78	21.23	19.84	19.16	17.98	16.63
T_{12}	93.67	87.33	86.00	85.33	84.67	14.48	14.16	13.17	12.05	10.51	21.24	19.92	19.10	18.27	17.50
T_{13}	94.33	91.33	89.33	87.33	85.67	14.55	14.30	13.40	12.35	10.63	21.31	20.34	19.63	18.92	17.61
T_{14}	94.33	91.33	91.67	88.33	87.33	14.64	14.23	13.78	12.86	11.82	22.83	22.32	20.89	20.06	18.86
Mean	**94.75**	**91.56**	**89.44**	**87.68**	**86.22**	**14.59**	**14.1**	**13.39**	**12.35**	**11.11**	**21.98**	**21.09**	**20.05**	**18.79**	**18.04**
S.Em±	**1.27**	**1.61**	**1.79**	**1.39**	**1.43**	**0.24**	**0.36**	**0.23**	**0.21**	**0.23**	**0.456**	**0.437**	**0.571**	**0.483**	**0.412**
CD(P=0.05)	**NS**	**NS**	**5.18**	**4.03**	**4.14**	**NS**	**NS**	**0.68**	**0.62**	**0.67**	**1.317**	**1.263**	**1.648**	**1.395**	**1.190**
CV (%)	**2.32**	**3.10**	**3.47**	**2.76**	**2.88**	**2.91**	**4.42**	**3.07**	**3.01**	**3.65**	**3.593**	**3.592**	**4.929**	**4.453**	**3.954**

Note: MAS: Months after storage **NS:** Non-significant

decline under vacuum and CO_2-enriched atmospheres indicates reduced respiration and oxidative losses, corroborating earlier findings in onion and rice seeds (Lamani *et al*., 2020). Seed moisture content increased progressively during storage, ranging from 5.50 to 6.26%, with minimum moisture retained under T_1(5.73%) and T_{10} (5.80%) and maximum under T_0 (6.26%) (Fig.2). Reduced moisture gain under modified atmospheres may be attributed to lower oxygen-mediated metabolic activity and restricted ROS generation, which otherwise accelerates deterioration (Apel & Hirt, 2004). Similar observations have been reported in soybean and green gram (Ibrahim *et al*., 1983; Meena *et al*., 2017).

Seed germination, seedling length and seedling dry weight declined with storage duration, but the rate of decline varied markedly among treatments (Plates 3). After ten months, the highest germination was recorded in T_{10} (90.33%), followed by vacuum storage (T_1: 88.33%), whereas atmospheric storage (T_0) resulted in

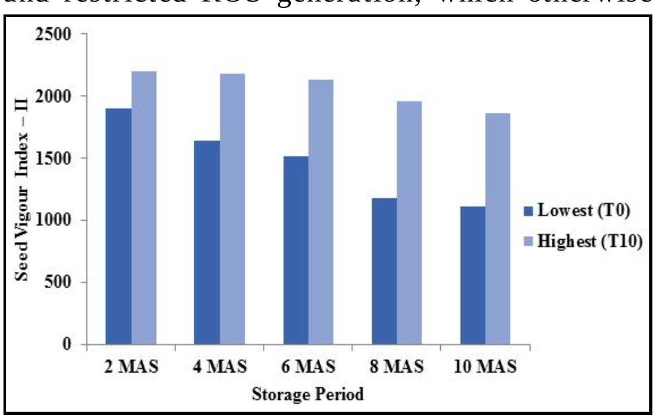

Fig. 7: Influence of modified atmospheric storage conditions on seed vigour index -II of capsicum seeds during storage.

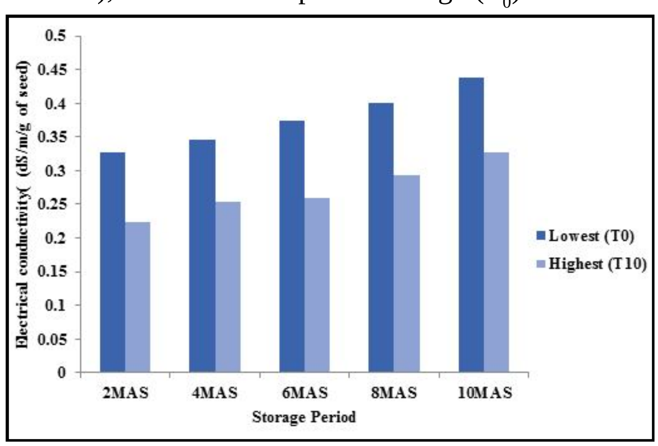

Fig. 8: Influence of modified atmospheric storage conditions on of electrical conductivity (dS/m/g of seed) capsicum seeds during storage.

Table 4: Influence of modified atmospheric storage conditions on seed vigour index I and IIof capsicum seeds during storage (Supplementary data).

Treatments	Seed Vigour Index - I					Seed Vigour Index - II				
	2MAS	4MAS	6MAS	8MAS	10MAS	2MAS	4MAS	6MAS	8MAS	10 MAS
T_0	1333	1223	1063	877	717	1901	1646	1516	1182	1114
T_1	1427	1356	1317	1213	1085	2155	2138	2068	1867	1819
T_2	1425	1345	1261	1146	1023	2125	2075	2007	1791	1719
T_3	1379	1316	1224	1081	988	2129	2024	1923	1746	1630
T_4	1362	1288	1182	1087	929	2060	1883	1789	1612	1457
T_5	1379	1295	1191	1056	922	2012	1856	1774	1681	1527
T_6	1370	1277	1182	1052	921	2090	1857	1796	1645	1532
T_7	1429	1371	1324	1240	1102	2187	2146	2111	1926	1840
T_8	1337	1295	1169	1016	888	2020	1730	1699	1569	1471
T_9	1371	1298	1170	1020	890	2080	1868	1789	1560	1505
T_{10}	1444	1391	1337	1274	1158	2202	2177	2135	1963	1868
T_{11}	1359	1276	1177	1052	938	1968	1862	1693	1564	1447
T_{12}	1383	1291	1181	1056	902	2025	1819	1725	1604	1482
T_{13}	1373	1319	1197	1061	897	1999	1857	1752	1640	1507
T_{14}	1381	1333	1263	1136	1032	2153	2068	1915	1772	1647
Mean	**1383**	**1311**	**1215**	**1091**	**959**	**2073**	**1933**	**1846**	**1674**	**1571**
S.Em±	**19.09**	**18.88**	**17.97**	**13.39**	**24.60**	**38.37**	**38.07**	**37.80**	**34.37**	**27.70**
CD(P=0.05)	**55.15**	**54.55**	**51.91**	**38.70**	**71.06**	**110.83**	**109.97**	**109.18**	**99.26**	**80.02**
CV(%)	**2.39**	**2.49**	**2.56**	**2.12**	**4.44**	**3.20**	**3.41**	**3.54**	**3.55**	**3.05**

Note: MAS: Months after storage **NS:** Non-significant

the lowest germination (77.67%), reflecting accelerated ageing under oxygen-rich conditions (Fig. 3). Mean seedling length was superior in T_{10} (13.08 cm) and T_7 (12.40 cm), while the shortest seedlings were observed in T_0 (9.24 cm) (Fig. 4). Similarly, seedling dry weight remained highest in T_{10} (20.88 mg) and T_7 (20.31 mg), compared to T_0 (14.34 mg) (Fig. 5). indicating better reserve utilization and membrane stability under modified atmospheres. These results are in agreement with reports of delayed seed deterioration under low oxygen and CO_2 enriched storage conditions (Manjunatha *et al*., 2016; Lamani *et al*., 2020).

Marked variation was also evident in seed vigour index-I and II after ten months of storage (Table 4). The highest SVI-I (1158) and SVI-II (1868) were recorded in T_{10}, followed by T_7, whereas atmospheric air (T_0) showed the lowest values (SVI-I: 717; SVI-II: 1113) (Fig.6 and Fig. 7). Enhanced vigour under anoxic and CO_2 enriched conditions is attributed to reduced oxidative stress, improved membrane integrity and slower reserve depletion, while oxygen-rich environments accelerate ROS-mediated damage and vigour loss. These findings corroborate earlier studies in seeds stored under modified atmospheric conditions (Hameed *et al*., 2013; Manjunatha *et al*., 2016; Lamani *et al*., 2020).

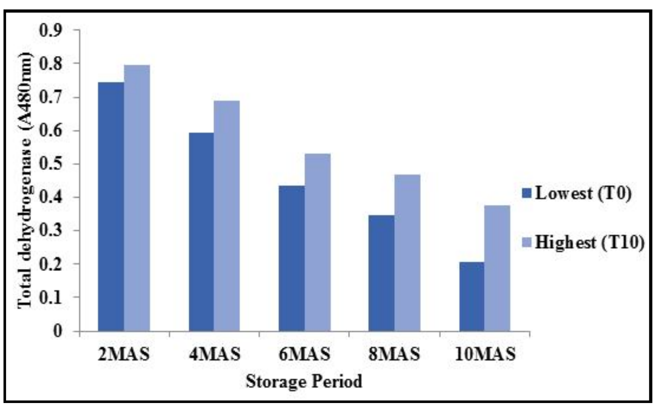

Fig. 9: Influence of modified atmospheric storage conditions on total dehydrogenase activity (A_{480}nm) of capsicum seeds during storage.

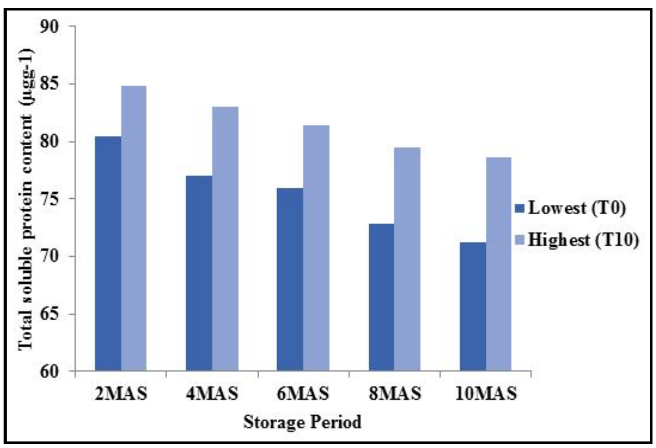

Fig. 10: Influence of modified atmospheric storage conditions on total soluble protein content (µgg^{-1}) of capsicum seeds during storage.

Table 5: Influence of modified atmospheric storage conditions on electrical conductivity (dS/m/g of seed) of capsicum seeds during storage (Supplementary data).

Treat-ments	ED					TD					TSPC				
	2 MAS	4 MAS	6 MAS	8 MAS	10 MAS	2 MAS	4 MAS	6 MAS	8 MAS	10 MAS	2 MAS	4 MAS	6 MAS	8 MAS	10 MAS
T_0	0.328	0.346	0.375	0.401	0.439	0.744	0.595	0.435	0.348	0.208	80.480	77.053	75.900	72.873	71.273
T_1	0.244	0.289	0.314	0.334	0.365	0.789	0.679	0.513	0.450	0.340	83.091	81.897	80.070	78.483	77.300
T_2	0.235	0.312	0.321	0.339	0.366	0.782	0.680	0.509	0.446	0.326	82.760	81.527	79.843	77.403	76.197
T_3	0.273	0.310	0.322	0.354	0.384	0.777	0.654	0.499	0.407	0.291	81.387	80.853	79.273	78.010	74.757
T_4	0.275	0.316	0.334	0.353	0.391	0.774	0.647	0.498	0.386	0.241	82.093	79.240	78.520	78.091	73.230
T_5	0.273	0.298	0.337	0.380	0.396	0.776	0.659	0.489	0.397	0.235	80.697	78.613	77.363	76.630	73.273
T_6	0.254	0.322	0.341	0.383	0.399	0.787	0.642	0.495	0.379	0.247	83.230	81.403	78.060	77.657	73.387
T_7	0.224	0.256	0.274	0.299	0.347	0.791	0.685	0.524	0.460	0.366	84.517	82.203	80.157	79.160	78.017
T_8	0.277	0.336	0.350	0.381	0.412	0.762	0.638	0.449	0.354	0.218	80.847	78.777	76.140	75.353	72.163
T_9	0.260	0.309	0.334	0.370	0.397	0.777	0.669	0.475	0.366	0.252	82.605	79.177	78.393	76.823	75.483
T_{10}	0.223	0.254	0.260	0.293	0.327	0.795	0.689	0.532	0.467	0.376	84.857	83.057	81.400	79.500	78.643
T_{11}	0.262	0.306	0.337	0.373	0.398	0.772	0.633	0.501	0.391	0.245	82.430	79.197	78.293	77.217	76.337
T_{12}	0.250	0.308	0.336	0.361	0.395	0.772	0.646	0.468	0.383	0.244	80.980	80.913	78.157	75.540	75.243
T_{13}	0.246	0.293	0.331	0.363	0.411	0.763	0.639	0.473	0.377	0.266	82.173	79.923	78.433	76.804	73.407
T_{14}	0.286	0.304	0.324	0.343	0.385	0.782	0.659	0.494	0.384	0.314	82.897	81.013	78.843	77.627	75.047
Mean	**0.261**	**0.304**	**0.326**	**0.355**	**0.387**	**0.776**	**0.654**	**0.490**	**0.400**	**0.278**	**82.336**	**80.323**	**78.590**	**77.145**	**74.917**
S.Em±	**0.006**	**0.008**	**0.008**	**0.006**	**0.005**	**0.011**	**0.009**	**0.010**	**0.008**	**0.007**	**1.248**	**1.088**	**1.272**	**1.816**	**1.362**
CD(P=0.05)	**0.017**	**0.023**	**0.023**	**0.018**	**0.015**	**0.032**	**0.025**	**0.028**	**0.023**	**0.019**	**3.604**	**3.142**	**3.673**	**5.245**	**3.934**
CV (%)	**3.930**	**4.628**	**4.116**	**3.020**	**2.277**	**2.502**	**2.300**	**3.411**	**3.513**	**4.180**	**2.625**	**2.346**	**2.803**	**4.077**	**3.149**

Note: MAS: Months after storage
EC: Electrical conductivity ((dS/m/g of seed); TD: Total dehydrogenase (A_{480}nm); TSPC: Total soluble protein content (μgg^{-1})

Influence of different storage conditions on biochemical seed quality parameters

Electrical conductivity (EC) increased progressively with storage duration across all treatments, indicating gradual membrane deterioration. The highest EC was consistently recorded under ambient storage (T_0), reaching 0.439 dS m^{-1} g^{-1} at 10 MAS (Fig. 8), whereas seeds stored under oxygen free, CO_2 enriched atmospheres, particularly 40% N_2 + 0% O_2 + 60% CO_2 (T_{10}) and 60% N_2 + 0% O_2 + 40% CO_2 (T_7) (Supplementary data Table 5), exhibited the lowest EC values, reflecting better membrane integrity. Increased EC is associated with solute leakage due to loss of membrane selectivity caused by oxidative damage and ROS accumulation (Basra, 2000). Similar trends were reported by Barzali *et al*., (2005) in rye, Capilheira *et al*., (2019) in soybean and Sivasakthi & Renugadevi (2020) in onion.

Dehydrogenase activity declined with storage

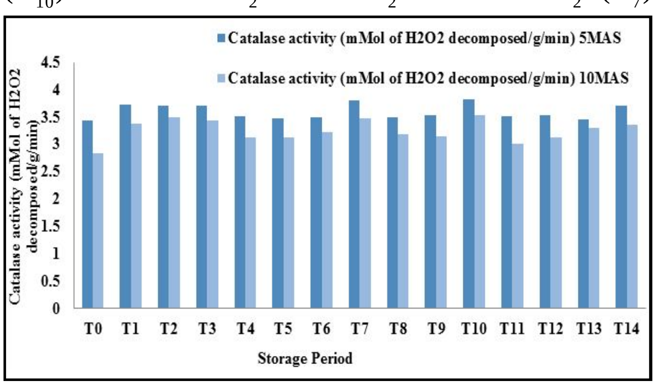

Fig. 11: Influence of modified atmospheric storage conditions on Catalase activity (mMol of H_2O_2 decomposed/g/min) of Capsicum seeds during storage.

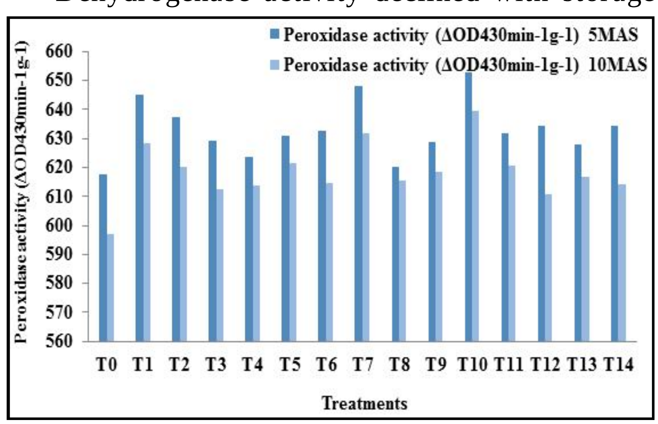

Fig. 12: Influence of modified atmospheric storage conditions on peroxidase activity (mMol of H_2O_2 decomposed/g/min) of capsicum seeds during storage.

Table 6: Influence of modified atmospheric storage on catalase activity (m Mol of H_2O_2 decomposed/g/min) and peroxidase ($\Delta OD_{430} min^{-1} g^{-1}$) of capsicum seeds during ten months of storage (Supplementary data).

Treatments	CA		PA	
	5 MAS	10 MAS	5 MAS	10 MAS
T_0	3.437	2.837	617.667	597.240
T_1	3.733	3.377	645.327	628.303
T_2	3.707	3.497	637.223	620.226
T_3	3.707	3.447	629.300	612.443
T_4	3.510	3.133	623.763	613.640
T_5	3.477	3.133	630.886	621.707
T_6	3.497	3.217	632.627	614.720
T_7	3.800	3.473	648.310	632.032
T_8	3.494	3.180	620.023	615.317
T_9	3.526	3.149	628.847	618.579
T_{10}	3.830	3.531	652.783	639.720
T_{11}	3.523	3.022	631.760	620.663
T_{12}	3.531	3.131	634.530	610.927
T_{13}	3.459	3.303	627.810	617.007
T_{14}	3.704	3.360	634.299	614.247
Mean	**3.596**	**3.266**	**633.010**	**618.451**
S.Em±	**0.050**	**0.060**	**14.012**	**14.122**
CD(P=0.05)	**0.146**	**0.172**	**40.469**	**40.789**
CV(%)	**2.427**	**3.167**	**3.834**	**3.955**

CA: Catalase activity (m Mol of H_2O_2 decomposed/g/min); PA: Peroxidase activity($\Delta OD_{430} min^{-1} g^{-1}$)
Note: MAS: Months after storage

duration, with the lowest activity recorded under ambient conditions (T_0: 0.208 A_{480}) and the highest under modified atmospheres, particularly T_{10} (0.376 A_{480}) and T_7 (0.366 A_{480}) at 10 MAS. Higher enzyme activity under CO_2-rich, oxygen-free storage indicates better preservation of mitochondrial respiration and seed viability (Rudrapal & Basu, 1970; Halder & Gupta, 1982). Similar improvements in enzyme activity under low-oxygen storage were reported in onion and pigeonpea (Sivasakthi & Renugadevi, 2020; Manjunatha *et al.*, 2016).

Total soluble protein content decreased steadily during storage, declining from 88.23 to 71.27 µg g^{-1}, with the lowest values under T_0 (71.27 µg g^{-1}) and higher retention under T_{10} (78.64 µg g^{-1}) and T_7 (78.02 µg g^{-1}) at 10 MAS. Protein degradation during storage is primarily attributed to ROS-mediated oxidative damage, leading to reduced vigour and viability (Ching & Schoolcraft, 1968; Hewrton, 1994; Tatipata, 2009; Halliwell & Gutteridge, 2007). Better protein preservation under CO_2-enriched atmospheres corroborates earlier findings in groundnut and sorghum (Gangadhara *et al.*, 2016; Punithavathi *et al.*, 2023).

Antioxidative enzymes such as catalase and peroxidase declined with storage period; however, modified atmospheres significantly slowed this reduction. Catalase activity was highest in T_{10} (3.531 mMol H_2O_2 g^{-1} min^{-1}) and T_7 (3.473 mMol H_2O_2 g^{-1} min^{-1}), while the lowest activity was observed in T_0 (2.837 mMol H_2O_2 g^{-1} min^{-1}). Similarly, peroxidase activity remained higher in T_{10} and T_7 compared to ambient storage, reflecting enhanced ROS scavenging capacity and delayed seed ageing. Comparable results under nitrogen or CO_2-enriched storage were reported by Sivasakthi & Renugadevi (2020), Punithavathi *et al.*, (2023) and Qu *et al.*, (2022).

Conclusion

These findings support the hypothesis that both initial seed quality and packaging material play a pivotalrole in determining seed health and storability. Aluminiumpouches, being impervious to air, moisture and vapour, provided an effective barrier against infestation and deterioration. The study demonstrated that modified atmospheric storage, particularly 40% N_2+ 0% O_2+ 60% CO_2 (T_{10}) and 60% N_2+ 0% O_2+ 40% CO_2 (T_7), was highly effective in preserving the physical, physiological and biochemical quality of hybrid capsicum seeds over ten months. These treatments consistently maintained higher germination, vigour indices, seedling growth and dry matter accumulation compared to atmospheric air (T0). Oxygen-free, CO_2-enriched environments minimized respiration, reduced moisture gain, and slowed deterioration of seed reserves. Biochemical traits such as electrical conductivity, dehydrogenase activity, soluble protein content, catalase and peroxidase activities were better retained under modified atmospheres, indicating lower oxidative stress and improved membrane stability. In contrast, ambient air caused rapid ageing due to ROS accumulation, resulting in poor vigour and enzyme activity. Across all treatments, seed health remained intact with zero mycoflora incidence. Overall, the findings confirm that MAP, especially high CO_2 and oxygen exclusion, offers a superior strategy for long-term storage of capsicum seeds.

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