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Effect of Modified Atmospheric Storage on Seed Longevity of Soybean [*Glycine max* (L.) Merr.]

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Seed quality is crucial for boosting seed production and productivity. However, soybean seeds are inherently short lived, quickly loses viability even under optimal storage conditions. Therefore, maintaining their quality during storage is of prime importance. Keeping these in view a laboratory experiment was conducted to study the effect of modified atmospheric storage on seed quality of soybean (*cv*. DSb 34). The freshly harvested seeds with initial moisture content of 7.6% were stored in different modified atmospheric gaseous combinations for nine months from November 2023-August 2024. Results indicated that the seeds stored with gaseous combination of 90 % CO_2: 4 % O_2: 6 % N_2 in 700 gauge polyethylene bag maintained better seed quality in terms of germination (86.77%), shoot length (14.49 cm), root length (12.58 cm), dry weight(0.995g/ 10 seedlings), seedling vigour index I (2349) and II (86.34) upto the end of nine months storage period by recording higher total dehydrogenase (0.438 OD value), α- amylase (10.72 µmol of maltose released min^{-1} ml^{-1} of enzyme) and catalase activity (1.364 µmol H_2O_2 decomposed $min^{-1}g^{-1}$ protein) compared to all other gaseous combinations and control. Hence, this technique can be used to maintain seed longevity with little deterioration, ensuring the quality of seeds even after extended storage period.

Keywords: Soybean; seed longevity; seed quality; quality seeds.

1. INTRODUCTION

Soybean [*Glycine max* (L.) Merr.]is a legume and oil seed crop native to East Asia, belongs to family *leguminaceae.* It is becoming an economically and industrially important crop as it possesses many therapeutical and nutraceutical compounds. Therefore, soybean is referred to as ‘Gold from the soil’ (Ramlal et al., 2024). The seeds are powerhouse of nutrients consisting of 40-45% protein, 20-22% oil and 20 to 26% carbohydrates (Rahman, et al., 2011). India ranks fifth among major soybean growing countries in the world with 13.08 m ha of cultivated area producing 14.98 m t at a productivity of 1298 kg/ha (Anonymous, 2023).

Quality seeds are fundamental input in agriculture. Insufficient access to high quality soybean seeds poses a significant obstacle for expanding soybean cultivation. Soybean seed is considered as poor storer, loses viability quickly when stored under ambient condition as compared to other *kharif* oil seed /pulse crops due to its inherent thin seed coat and high fatty acids. In addition to these intrinsic factors, the composition of the surrounding atmospheric air during ambient storage also significantly effects seed longevity. Oxygen levels in the air stimulate metabolic activity in seeds, as well as in insects and microorganisms, accelerating deleterious oxidative processes leading to an accumulation of reactive oxygen species (ROS), ultimately reducing seed viability and physiological quality. Low O_2 and high CO_2 during storage environment reduced metabolic activity favoring quality maintenance of soybean seed (Alencar, et al., 2010). Hence, Modified atmospheric storage (MAS) or storage of seeds with elevated levels of carbon dioxide emerges as a pivotal solution in this regard.

Modified atmospheric storage is one of the seed and food preservation method that maintains the natural quality of seeds and food products besides extending the storage life of seed by reducing the respiration rate (Moltos, et al., 2002). MAS is, modifying the concentration of the storage gases like carbon dioxide, oxygen and nitrogen, which creates an environment different from an atmospheric air condition. Modified atmosphere of elevated carbon dioxide and depleted oxygen is an effective method against insect pests and microorganisms attack and seed quality deterioration during storage. MAS slows down the respiration rates of seeds and reduces the insect and micro-organisms activity during seed storage (Jayas, et al., 2002). MAS with addition of CO_2 inside the hermetic packages favors the maintenance of the physiological quality of soybean seeds during storage (Capilheira, et al., 2019).

Keeping in view the above facts the present investigation was undertaken to understand the effect modified atmospheric storage on seed longevity of soybean [*Glycine max* (L.) Merrill]”

2. MATERIALS AND METHODS

The laboratory experiment was conducted in the Seed testing laboratory, Seed Unit and Post Graduate laboratory, Department of Seed Science and Technology, College of Agriculture, Dharwad during November 2023- August 2024.

For the conduct of experiment, freshly harvested 500 g of soybean seeds (*cv*. DSb 34) with 7.6 % moisture content were packed in 700 gauge polythene bag with different concentrations of CO_2, O_2 and N_2 using MAC VAC DUO machine according to treatments in three replications. The packed seeds stored for nine months from November 2023 to August 2024 in Department of Seed Science and Technology, College of Agriculture, Dharwad. The treatments include different concentrations of CO_2, O_2 and N_2 as mentioned under.

2.1 Method of Modified Atmospheric Packaging

For the packaging MAP VAC DUO machine of Elixir Technology was used (Plate1a.). The detailed procedure of modified atmospheric packaging is given below

- Initially the gas cylinders of CO_2, O_2 and N_2were opened, releasing gas at a pressure of 7 kg per cm². The released gases are filtered by the dust and mist filters (Plate1b.).
- The required combinations of CO_2, O_2 and N_2 were mixed in the digital 3 G gas mixing chamber (Plate1c.).
- 500 grams of soybean seeds were weighed and filled in 700 gauge polythene bag. The filled polythene bag kept in sealing chamber and closed.
- Later, the gas inlet evacuates the air from the polyethylene bag and flushes in the required concentration of gases, which are mixed in the mixing chamber
- Subsequently, sealing chamber automatically seals the packet (Plate1d.).

2.2 Effect of Modified Atmospheric Storage on Seed Quality Parameters of Soybean During Storage

Seeds stored under different concentrations of CO_2, O_2 and N_2 gases along with T_{13}, T_{14} and T_{15}were used for analysis of following seed quality parameters bimonthly for nine months of storage.

The standard germination test was conducted by adopting between paper methodaccording to ISTA rules for seed testing (ISTA, 2013). The final germination count was recorded on Eighth day and percent germination calculated using following formula:

Seed germination (%) = Number of normal seedlings /Total number of seeds kept for germination × 100

From the germination test, Ten normal seedlings were randomly selected from each treatment in Four replications of on Eighth day of germination test and shoot length, root length and seedling dry weight (80 ℃ for 24 hours) were measured.

The seedling vigour index- I and II was calculated using the formula stated by Abdul-Baki and Anderson (Abdul-Baki and Anderson, 1973).

Seedling Vigour Index I = Germination (%) × [Mean Shoot Length (cm) + Mean Root Length (cm)]

Seedling Vigour Index II = Germination (%) **×** Mean seedling dry weight (g/ 10 seedlings)

List 1. Concentrations of CO_2, O_2&N_2used for modified atmospheric storage

Sl. No.	Concentration of gases (%)		
	CO_2	**O_2**	**N_2**
T_1	95	2	3
T_2	90	4	6
T_3	85	6	9
T_4	80	8	12
T_5	75	10	15
T_6	70	12	18
T_7	65	14	21
T_8	60	16	24
T_9	55	18	27
T_{10}	50	20	30
T_{11}	100	0	0
T_{12}	0	0	100
T_{13}	Atmospheric air (Polythene bag)		
T_{14}	Vacuum packaging		
T_{15}	Control (HDPE bag)		

a. MAP VAC DUO machine b. CO_2, O_2, N_2 gas cylinders

c. Gas mixing chamber d. Sealing chamber

Plate 1. Method of modified atmospheric packaging using MAP VAC DUO machine

2.3 Effect of Modified Atmospheric Storage on Enzymatic Activities of Soybean During Storage

Seeds stored under different concentrations of CO_2, O_2 and N_2 gases were used for analysis and the following biochemical parameters were analysed for Nine months ofstorage during initial, mid and final months of storage.

Dehydrogenase activity was determined by using tetrazolium staining method. The OD value obtained was recorded as the dehydrogenase enzyme activity (Kittock, 1968). α-Amylase activity was analyzed according to Sadasivam and Manickam (Sadasivam and Manickam, 1996). Catalase activity was estimated by the decrease in absorbance of H_2O_2 at 240 nm and expressed as μmol H_2O_2 decomposed/min/g (Aebi, 1984).

3. RESULTS

3.1 Effect of Modified Atmospheric Storage on Seed Quality Parameters of Soybean During Storage

The results of the present experiment revealed that, all the seed quality parameters decreased with advancement of storage period, irrespective of modified atmospheric storage conditions, though the decline varied across the treatments. Seed quality parameters differed significantly in all the months of storage due to modified atmospheric storage and untreated control.

The mean initial seed germination (93.25 %) declined to 74.08 per cent at the end of the storage period. Among the different modified atmospheric storage conditions, maximum seed germination of 86.77 % was recorded in gaseous combination 90 % CO_2: 4 % O_2: 6 % N_2 (T_2) which was on par with T_1: 95 % CO_2: 2 % O_2: 3 % N_2 (85.62 %) and T_{11}: 100 % CO_2: 0 % O_2: 0 % N_2 (85.10 %) followed by T_{12}: 0 % CO_2: 0 % O_2: 100 % N_2 (83.18 %). Seeds stored in HDPE bag with atmospheric air (T_{15}: Control) recorded significantly lower seed germination percentage of 50.35 % at the end of nine months storage (Table 1).

The maximum shoot length (14.49 cm) and root length (12.58 cm) were recorded in MAS condition of 90 % CO_2: 4 % O_2: 6 % N_2 (T_2) which was on par with T_1: 95 % CO_2: 2 % O_2: 3 % N_2 (14.32 cm and 12.47 cm respectively) and T_{11}: 100 % CO_2: 0 % O_2: 0 % N_2 (14.25 cm and 12.44 cm respectively) followed by T_{12}: 0 % CO_2: 0 % O_2: 100 % N_2 (13.45 cm and 11.75 cm respectively). Seeds stored in HDPE bag with atmospheric air (T_{15}: Control) recorded significantly lower shoot length (9.61cm) and root length (8.03 cm) at the end of storage period (Table 2 & 3). Seedling dry weight was also followed the similar trend (Table 4).

At the end of nine months storage, maximum seedling vigour index I (2349) was observed in gaseous combination of 90 % CO_2: 4 % O_2: 6 % N_2 (T_2) followed by T_1: 95 % CO_2: 2 % O_2: 3 % N_2 (2294) whereas, significantly lower vigour index (744) was recorded in seeds stored in HDPE bag with atmospheric air (T_{15}: Control). The similar trend was also followed by seedling vigour index II (Fig 1).

3.2 Effect of Modified Atmospheric Storage on Enzymatic Activities of Soybean During Storage

The enzymes activities *viz.*, dehydrogenase, α amylase and catalase showed a positive correlation with seed quality during storage. Initially enzymes activities were maximum of 0.648 OD value, 11.28 µmol of maltose released min^{-1} ml^{-1} of enzyme and 1.428 µmol H_2O_2 decomposed $min^{-1}g^{-1}$ protein, while it was reduced to 0.189 OD value, 9.66 µmol of maltose released min^{-1} ml^{-1} of enzyme and 1.212 µmol H_2O_2 decomposed $min^{-1}g^{-1}$ protein as the storage period progressed, respectively. At the end nine months of storage, seeds stored in 90 % CO_2: 4 % O_2: 6 % N_2 (T_2) recorded maximum enzyme activities which was on par with T_1: 95 % CO_2: 2 % O_2: 3 % N_2, whereas it was minimum in the seeds stored in HDPE bagwith atmospheric air (T_{15}: Control) (Table 5- Table 7).

Table 1. Effect of Modified Atmospheric Storage (MAS) on seed germination (%) of soybean (*cv*. DSb 34) during storage

Sl. No.	Concentration of gases (%)			Months of storage (Nov 2023- Aug 2024)					
	CO_2	O_2	N_2	0 (Nov)	2 (Jan)	4 (Mar)	6 (May)	8 (Jul)	9 (Aug)
T_1	95	2	3	93.25	92.49	91.25	89.81	87.79	85.62
T_2	90	4	6	93.25	92.64	91.45	90.21	88.53	86.77
T_3	85	6	9	93.25	91.17	87.68	85.07	82.96	78.63
T_4	80	8	12	93.25	90.85	87.49	84.59	80.15	76.54
T_5	75	10	15	93.25	90.33	86.79	84.01	79.63	74.72
T_6	70	12	18	93.25	90.17	86.56	83.58	79.05	73.63
T_7	65	14	21	93.25	90.05	84.65	80.44	76.86	71.85
T_8	60	16	24	93.25	89.86	83.58	77.95	73.15	68.52
T_9	55	18	27	93.25	89.58	82.45	76.28	71.75	67.50
T_{10}	50	20	30	93.25	89.49	81.35	75.54	70.02	66.06
T_{11}	100	0	0	93.25	92.38	91.15	89.63	87.58	85.10
T_{12}	0	0	100	93.25	92.06	90.28	88.17	86.49	83.18
T_{13}	Atmospheric air (Polythene bag)			93.25	88.55	80.90	74.06	68.84	60.73
T_{14}	Vacuum packaging			93.25	91.84	90.01	87.84	85.89	82.06
T_{15}	Control (HDPE bag)			93.25	88.13	75.85	69.02	61.85	50.35
Mean				93.25	90.64	86.10	82.41	78.70	74.08
S.Em ±					0.086	0.098	0.207	0.238	0.347
CD (0.01)					0.275	0.314	0.662	0.967	1.405

HDPE: High Density Polyethylene bag

Table 2. Effect of Modified Atmospheric Storage (MAS) on shoot length (cm) of soybean (*cv*. DSb 34) during storage

Sl. No.	Concentration of gases (%)			Months of storage (Nov 2023- Aug 2024)					
	CO_2	O_2	N_2	0 (Nov)	2 (Jan)	4 (Mar)	6 (May)	8 (Jul)	9 (Aug)
T_1	95	2	3	16.08	15.90	15.65	15.32	14.92	14.32
T_2	90	4	6	16.08	15.95	15.72	15.41	15.08	14.49
T_3	85	6	9	16.08	15.68	15.15	14.48	13.72	13.06
T_4	80	8	12	16.08	15.65	15.01	14.25	13.56	12.85
T_5	75	10	15	16.08	15.64	14.87	14.13	13.32	12.51
T_6	70	12	18	16.08	15.61	14.78	13.95	13.04	12.13
T_7	65	14	21	16.08	15.58	14.64	13.81	12.86	11.92
T_8	60	16	24	16.08	15.55	14.47	13.60	12.63	11.60
T_9	55	18	27	16.08	15.53	14.24	13.35	12.36	11.43
T_{10}	50	20	30	16.08	15.50	14.02	13.01	12.12	11.18
T_{11}	100	0	0	16.08	15.87	15.59	15.24	14.85	14.25
T_{12}	0	0	100	16.08	15.75	15.35	14.83	14.18	13.45
T_{13}	Atmospheric air (Polythene bag)			16.08	15.45	13.87	12.55	11.64	10.58
T_{14}	Vacuum packaging			16.08	15.71	15.28	14.66	13.96	13.32
T_{15}	Control (HDPE bag)			16.08	15.38	13.74	12.11	10.78	9.61
Mean				16.08	15.65	14.83	14.05	13.27	12.45
S. Em ±					0.021	0.033	0.047	0.062	0.065
CD (0.01)					0.081	0.130	0.181	0.238	0.252

HDPE: High Density Polyethylene bag

Table 3. Effect of Modified Atmospheric Storage (MAS) on root length (cm) of soybean (*cv*. DSb 34) during storage

Sl. No.	Concentration of gases (%)			Months of storage (Nov 2023- Aug 2024)					
	CO_2	O_2	N_2	0 (Nov)	2 (Jan)	4 (Mar)	6 (May)	8 (Jul)	9 (Aug)
T_1	95	2	3	14.76	14.47	14.29	13.70	13.14	12.47
T_2	90	4	6	14.76	14.50	14.33	13.75	13.21	12.58
T_3	85	6	9	14.76	14.02	13.39	12.91	12.30	11.43
T_4	80	8	12	14.76	13.98	13.20	12.73	12.17	11.26
T_5	75	10	15	14.76	13.95	13.15	12.64	12.02	11.09
T_6	70	12	18	14.76	13.87	13.03	12.56	11.89	10.98
T_7	65	14	21	14.76	13.85	12.95	12.41	11.77	10.75
T_8	60	16	24	14.76	13.78	12.82	12.32	11.62	10.57
T_9	55	18	27	14.76	13.75	12.64	12.16	11.55	10.41
T_{10}	50	20	30	14.76	13.61	12.32	11.95	11.38	10.21
T_{11}	100	0	0	14.76	14.45	14.27	13.68	13.11	12.44
T_{12}	0	0	100	14.76	14.36	13.75	13.40	12.61	11.75
T_{13}	Atmospheric air(Polythene bag)			14.76	13.53	12.17	11.35	10.84	9.91
T_{14}	Vacuum packaging			14.76	14.32	13.58	13.18	12.49	11.61
T_{15}	Control (HDPE bag)			14.76	13.46	11.88	11.02	10.28	8.03
Mean				14.76	13.99	13.18	12.65	12.03	11.03
S. Em ±					0.011	0.016	0.021	0.029	0.040
CD (0.01)					0.042	0.061	0.080	0.110	0.152

HDPE: High Density Polyethylene bag

Table 4. Effect of Modified Atmospheric Storage (MAS) on seedling dry weight (g/ 10 seedlings) of soybean (*cv*. DSb 34) during storage

Sl. No.	Concentration of gases (%)			Months of storage (Nov 2023- Aug 2024)					
	CO_2	O_2	N_2	0 (Nov)	2 (Jan)	4 (Mar)	6 (May)	8 (Jul)	9 (Aug)
T_1	95	2	3	1.093	1.083	1.075	1.056	1.033	0.989
T_2	90	4	6	1.093	1.085	1.076	1.058	1.037	0.995
T_3	85	6	9	1.093	1.058	1.049	1.024	0.989	0.943
T_4	80	8	12	1.093	1.055	1.045	1.019	0.972	0.923
T_5	75	10	15	1.093	1.052	1.041	1.014	0.954	0.901
T_6	70	12	18	1.093	1.049	1.039	1.011	0.948	0.885
T_7	65	14	21	1.093	1.046	1.035	0.995	0.916	0.859
T_8	60	16	24	1.093	1.042	1.032	0.991	0.881	0.823
T_9	55	18	27	1.093	1.039	1.027	0.986	0.874	0.811
T_{10}	50	20	30	1.093	1.035	1.020	0.979	0.852	0.779
T_{11}	100	0	0	1.093	1.082	1.073	1.054	1.029	0.986
T_{12}	0	0	100	1.093	1.072	1.060	1.048	1.015	0.971
T_{13}	Atmospheric air (Polythene bag)			1.093	1.031	1.015	0.971	0.822	0.708
T_{14}	Vacuum packaging			1.093	1.070	1.058	1.045	1.008	0.962
T_{15}	Control (HDPE bag)			1.093	1.030	1.011	0.965	0.793	0.577
Mean				1.093	1.055	1.044	1.014	0.942	0.874
S.Em ±					0.001	0.001	0.001	0.002	0.003
CD (0.01)					0.003	0.003	0.004	0.008	0.011

HDPE: High Density Polyethylene bag

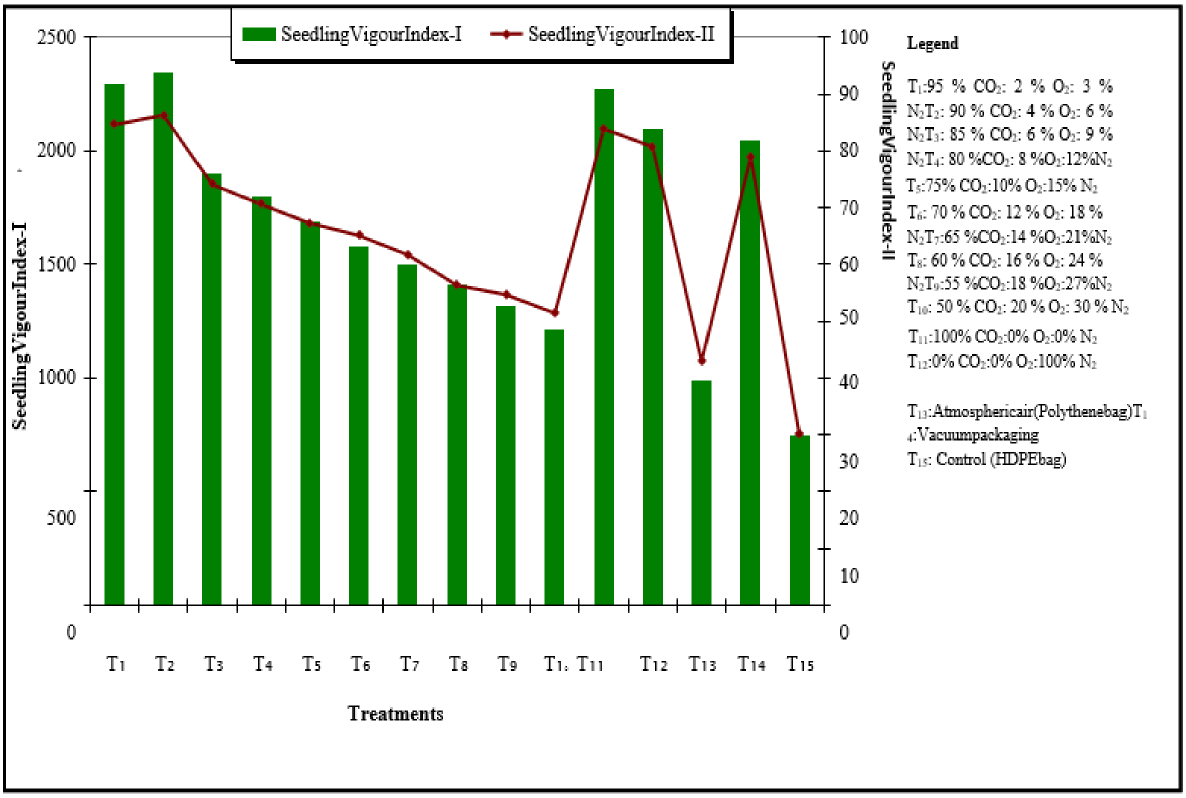

Fig. 1. Effect of Modified Atmospheric Storage (MAS) on seedling vigourindices of soybean (cv.DSb34) during storage

Table 5. Effect of Modified Atmospheric Storage (MAS) on total dehydrogenase activity (OD Value) of soybean (*cv*. DSb 34) during storage

Sl. No.	Concentration of gases (%)			Months of storage (Nov 2023- Aug 2024)		
	CO_2	O_2	N_2	0 (Nov)	5 (Apr)	9 (Aug)
T_1	95	2	3	0.648	0.590	0.430
T_2	90	4	6	0.648	0.593	0.438
T_3	85	6	9	0.648	0.558	0.387
T_4	80	8	12	0.648	0.549	0.384
T_5	75	10	15	0.648	0.535	0.371
T_6	70	12	18	0.648	0.514	0.357
T_7	65	14	21	0.648	0.496	0.341
T_8	60	16	24	0.648	0.477	0.329
T_9	55	18	27	0.648	0.467	0.294
T_{10}	50	20	30	0.648	0.455	0.273
T_{11}	100	0	0	0.648	0.588	0.425
T_{12}	0	0	100	0.648	0.575	0.412
T_{13}	Atmospheric air(Polythene bag)			0.648	0.431	0.248
T_{14}	Vacuum packaging			0.648	0.570	0.409
T_{15}	Control (HDPE bag)			0.648	0.418	0.189
Mean				0.648	0.521	0.352
S.Em ±					0.003	0.003
CD (0.01)					0.011	0.011

HDPE: High Density Polyethylene bag

Table 6. Effect of Modified Atmospheric Storage (MAS) on α- amylase activity (μmol of maltose released min $^{-1}$ ml^{-1} of enzyme) of soybean (*cv*. DSb 34) during storage

Sl. No.	Concentration of gases (%)			Months of storage (Nov 2023- Aug 2024)		
	CO_2	O_2	N_2	0 (Nov)	5 (Apr)	9 (Jul)
T_1	95	2	3	11.28	11.01	10.68
T_2	90	4	6	11.28	11.04	10.72
T_3	85	6	9	11.28	10.80	10.22
T_4	80	8	12	11.28	10.73	9.87
T_5	75	10	15	11.28	10.62	9.68
T_6	70	12	18	11.28	10.56	9.59
T_7	65	14	21	11.28	10.49	9.44
T_8	60	16	24	11.28	10.41	9.21
T_9	55	18	27	11.28	10.37	9.09
T_{10}	50	20	30	11.28	10.28	8.86
T_{11}	100	0	0	11.28	10.99	10.64
T_{12}	0	0	100	11.28	10.91	10.53
T_{13}	Atmospheric air (Polythene bag)			11.28	9.94	8.28
T_{14}	Vacuum packaging			11.28	10.87	10.46
T_{15}	Control (HDPE bag)			11.28	9.74	7.62
Mean				11.28	10.58	9.66
S.Em ±					0.002	0.003
CD (0.01)					0.006	0.009

HDPE: High Density Polyethylene bag

Table 7. Effect of Modified Atmospheric Storage (MAS) on catalase activity (µmol H_2O_2decomposed min^{-1} g^{-1} of protein) of soybean (*cv*. DSb 34) during storage

Sl. No.	Concentration of gases (%)			Months of storage (Nov 2023- Aug 2024)		
	CO_2	O_2	N_2	0 (Nov)	5 (Apr)	9 (Aug)
T_1	95	2	3	1.428	1.415	1.358
T_2	90	4	6	1.428	1.419	1.364
T_3	85	6	9	1.428	1.380	1.301
T_4	80	8	12	1.428	1.373	1.268
T_5	75	10	15	1.428	1.365	1.245
T_6	70	12	18	1.428	1.358	1.228
T_7	65	14	21	1.428	1.352	1.209
T_8	60	16	24	1.428	1.340	1.187
T_9	55	18	27	1.428	1.335	1.168
T_{10}	50	20	30	1.428	1.318	1.141
T_{11}	100	0	0	1.428	1.413	1.351
T_{12}	0	0	100	1.428	1.404	1.334
T_{13}	Atmospheric air (Polythene bag)			1.428	1.236	0.895
T_{14}	Vacuum packaging			1.428	1.399	1.321
T_{15}	Control (HDPE bag)			1.428	1.204	0.811
Mean				1.428	1.354	1.212
S.Em ±					0.002	0.004
CD (0.01)					0.006	0.015

HDPE: High Density Polyethylene bag

4. DISCUSSION

In modified atmospheric storage condition, the seeds stored in lower levels of oxygen and higher carbon dioxide concentrations shown higher retention of seed viability during storage period.The differences in storability of seeds is due to the variations in the gas concentrations, where the treatment T_2 (90 % CO_2 + 4 % O_2 + 6 % N_2) with higher CO_2 and lower oxygen concentration has recorded maximum germination during storage. Higher the levels of carbon dioxide present inside the package, better the maintenance of seed germination, since metabolism during storage is reduced due to decrease in oxygen concentration, thereby maintaining seed viability for a longer period of time (Mussi, 2005). The germination capacity has retained, when seeds were stored in an oxygen-depleted atmosphere which was associated with the inhibition of oxygen-dependent enzymatic activities, allowing greater mobilization of seed reserves for seedling formation has been observed in soybean (Ludwig, et al., 2021). Similar findings also reported by Capilheriaet al., (2019), Raghupathiet al., (2021) and Bhattarai et al., (2023).

In the present investigation, storage of soybean in high CO_2 concentration coupled with lower O_2 concentrations has been beneficial in maintaining the seedling growth, dry weight and vigour during storage. Seeds stored in elevated carbon dioxide environment within moisture proof containers exhibited high seedling vigour even after 3-5 years of ambient storage. The modified atmosphere storage with carbon dioxide proved superior to air- sealed storage, effectively preserving seed vigour over time (Doijode, 2006). Copeland (1985) emphasized the detrimental effects of seed deterioration, which include membrane degradation, the buildup of toxic metabolites, reduced enzymatic activity, lipid auto-oxidation, and the failure of repair mechanisms. These changes can lead to genetic degradation, lower yields, and ultimately, the loss of germination or death. In case of soybean storage, seeds exposed to atmospheric air are vulnerable to auto-oxidation and lipid peroxidation because of high oxygen levels in the air. This process generates free radicals and hydrogen peroxide, which damage cell structures and result in poor seed viability and vigour. The declining seedling vigour could be attributed to oxidative stress, which triggers the generation of reactive oxygen species (ROS). These ROS lead to lipid peroxidation, producing reactive aldehydes like malondialdehyde (MDA) and 4-hydroxynonenal (HNE) as end products. These compounds disrupt cellular metabolism, reducing

ATP production, which is essential for the growth and development of the seedling (Islavath, 2022). Similar findings were also reported by Anuja et al., (2014) and Divya et al., (2016).

Seeds are naturally inbuilt with the various kinds of enzymatic and non enzymatic antioxidants, which play a crucial role in prolonging seed longevity. In general, ageing is characterized by decrease of metabolic activity and an increase in catabolic processes. Seed deterioration during storage can lead to significant changes in the content and activity of enzymes responsible for utilizing stored reserves (Vasudevan et al., 2014). The better maintenance of vigour and viability in the seeds stored in modified atmospheric storage confirms a direct correlation between seed germination and enzyme activity. Similar results were also reported by Bera et al., (2004), Manjunatha et al., (2016) and Punithavathiet al., (2023).

5. CONCLUSION

The results of modified atmospheric storage effect on seed longevity of soybean confirmed that, all the seed quality attributes and enzyme activities were higher under the modified atmospheric storage conditions of 90 % CO_2, 4 % O_2, and 6 % N_2 throughout the nine-months storage period. This demonstrates that, this gaseous combination has a markedly positive impact on preserving the quality and vigourof soybean seeds compared to control condition. In conclusion, storing soybean seeds under modified atmospheric conditions characterized by high CO_2 and low O_2 level proves to be the most effective method for maintaining seed longevity by minimizing the seed deterioration.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc have been used during writing or editing of this manuscript. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology.

Details of the AI usage are given below:

1. Author(s) hereby declare that generative AI technologies such as ChatGPT, version- ChatGPT-4, Model- GPT-4, Source- OpenAI have been used during editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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