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Assessment of Packaging Materials for Bulk Packaging of Mustard

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

A study was conducted to develop effective bulk packaging solutions for mustard, focusing on testing various packaging materials with liners and analysing shelf life for export purposes. To maintain the quality of spices, it is crucial to have oxygen and gas barrier properties to preserve aroma. To address this, a novel liner combination has been introduced to evaluate its effectiveness in extending the shelf life of mustard. Mustard was packed in nine types of packaging materials selected based on sustainability aspects and subjected to accelerated climatic conditions (38±1°C and 90±2% RH) for six months. Physico-chemical parameters were measured in triplicate. Throughout the exposure period, moisture content and water activity in the mustard increased exponentially. Significant changes in colour, aroma, and microbial growth were observed in samples packaged in PP woven bags without liners and multiwall paper bags. However, no damage to the packaging materials was noted during transport testing. The maximum shelf life was recorded for mustard packed in PP woven bags with liners and multiwall paper bags with aluminium foil. Hence, the results indicated that exploring advanced liner combinations can significantly enhance the shelf life and maintain the quality of mustard.

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Keywords: Mustard; packaging; shelf life; sustainable; bulk.

1. INTRODUCTION

India stands as the preeminent global leader in spice production, holding the title of the largest producer, consumer, and exporter of spices worldwide. In the period spanning 2023 to February 2024, India achieved remarkable success in the international spice market, exporting spices valued at an impressive US$ 3.67 billion, according to the India Brand Equity Foundation (IBEF) [1] 2024 report and Spices Board's Trade Information Services [2]. Despite this substantial production capacity, there remains a notable gap in the attention given to the packaging of these spices. Spices, by their very nature, are typically shelf-stable due to their low moisture content, which halts respiration processes. However, biochemical, microbial, and other forms of degradation can still occur, influenced heavily by the conditions under which they are stored. Consequently, selecting the appropriate packaging material and type is crucial to preserving the quality and extending the shelf life of spices. Mustard seeds, a prominent member of the *Cruciferae* or *Brassicaceae* family, exemplify their importance and need for careful packaging. This plant family is well known for its culinary applications, therapeutic benefits, and unique flavour characteristics. It is particularly distinguished by its organosulfur compounds, which are integral to the mustard's distinctive pungency and flavour profile [3,4]. Thus, understanding and addressing the specific packaging needs of spices like mustard is essential to maintaining their quality and efficacy throughout their logistics and storage.

Whole spices are typically exported in bulk, where they are subsequently processed, ground, and blended into finished spice products. In this context, bulk packaging of mustard seeds plays a vital role within the spice supply chain, given mustard's importance as both a key culinary ingredient and a high-value commodity (Singh and Bansal, 2020). Effective protection for whole spices focuses on preventing moisture ingress and insect infestation. When stored as whole spices, flavour loss is minimal because the volatile oils are securely contained within the plant cells. Flexible packaging materials such as plastic films, pouches, woven bags, paper, and jute bags with plastic liners are commonly used for packaging both raw and whole spices, whether for consumer or institutional use [5,6]. Notably, the packaging industry in India is undergoing a significant shift towards more sustainable practices, driven by new regulations, changing consumer preferences, and innovative solutions. By embracing sustainable packaging designs, spice and packaging companies can both lessen their environmental impact and boost their appeal in the global market.

To tackle these challenges, the Indian Institute of Packaging (IIP) in Mumbai has conducted a study aimed at developing effective bulk packaging solutions for mustard, funded by the Spices Board of India under the Ministry of Commerce and Industry. This study involved testing various packaging materials and evaluating their impact on the shelf life of mustard for export markets.

2. MATERIALS AND METHODS

The packaging of the mustard was carried out at the R&D Department laboratory of the Indian Institute of Packaging, Mumbai. The whole mustard seeds were sourced from M/s Jabs International Private Limited, Navi Mumbai, and the packaging materials as specified by IIP were manufactured and supplied by M/s Shree Ganesh FIBC Private Limited, Ankleshwar, Gujarat; M/s Paper Bag Mfg. Co., Mumbai; and M/s Vishakha Polyfab Private Limited, Gujarat. For the packaging, both PP woven bags and multi-wall paper bags with various liners have been selected. Details of these materials are listed below:

P1: PP Woven Bag without Liner

P2: PP Woven Bag with Liner I (PE/EVOH/PE – 5 Ply; 50-60 µ)

P3: PP Woven Bag with Liner II (PA/EVOH/PE – 5 Ply; 50-60 µ)
P4: PP Woven Bag with Liner III (PE/EVOH/PE – 9 Ply; 70- 80 µ)
P5: PP Woven Bag with Liner IV (PA/EVOH/PE – 9 Ply; 70- 80 µ)
P6: Multi-wall Paper Bag (MET PET)
P7: Multi-wall Paper Bag (Aluminium foil)
P8: Multi-wall Paper Bag (with Lamination)
P9: Multi-wall Paper Bag – Control

The packaging materials were evaluated for their physical, mechanical, and physico-chemical properties to assess their quality

Table 1. Specifications of PP Woven ba

Sr. no.	Parameter	Unit	PP Woven bag
1	Breaking load	N	
	D1		739.40
	D2		396.60
2	Elongation	%	
	D1		14.32
	D2		16.48
3	Seam Strength	Kgf	21.23
4	Mass	gram	28.70
5	Length	cm	37.90
6	Width	cm	29.00
7	Ash	%	7.30
8	Thickness	µm	122.00

D1: Direction 1; D2: Direction 2

Table 2. Specification of Liners

Sr. No.	Parameters	Unit	Liner I (PE/EVOH/PE – 5 Ply; 50-60 µ)	Liner II (PA/EVOH/PE – 5 Ply; 50-60 µ)	Liner III (PE/EVOH/PE – 9 Ply; 70- 80 µ)	Liner IV (PA/EVOH/PE – 9 Ply; 70- 80 µ)
1	Thickness	(µm)	61	63	72	73
2	Elongation (%)	(%)				
	D1		511.99	348.81	556.65	398.42
	D2		328.86	329.6	360.12	276.15
3	Tensile Strength	(N/mm²)				
	D1		17.72	21.38	17.37	28.35
	D2		18.47	22.72	22.74	30.58
4	Break stress	(N/mm²)				
	D1		15.54	16.14	15.85	25.95
	D2		16.10	21.41	17.94	25.54
5	Break strain	(%)				
	D1		511.12	562.32	517.60	407.59
	D2		499.32	376.79	335.65	305.02
6	Bottom seal	(N)	26.82	31.45	29.51	45.07
7	Oxygen Transmission Rate	cc/m^2 for 24 hours	1.47	1.20	1.19	1.16
8	Water Vapour Transmission Rate	g/m^2 for 24 hours	3.91	3.44	3.51	2.60
9	Migration	(mg/kg)	0.030	0.031	0.036	0.037

D1: Direction 1; D2: Direction 2

Table 3. Specifications of 4 Ply Multiwall Paper Sack with Aluminium Foil, MET PET, with Poly Liner and without Poly Liner

Sl. No.	Parameters	Details of each layer	Multiwall Paper Bag (Aluminium foil)	Multiwall Paper Bag (MET PET)	Multiwall Paper Bag (with Lamination)	Multiwall Paper Bag (without Lamination)
1.	GSM	Outer Ply	78.84	77.72	79.48	78.58
		2nd Ply	78.07	77.40	74.45	71.01
		3rd Ply	78.43	77.89	76.42	71.90
		Inner Ply	118.82	111.37	94.95	71.27
2.	Burst Factor	Outer Ply	54.54	55.33	54.11	53.94
		2nd Ply	55.72	56.85	55.07	68.29
		3rd Ply	54.83	55.85	55.62	61.31
		Inner Ply	34.09	46.70	55.31	59.63
3.	Total bursting strength (kg/cm^2)	-	17.13	14.20	15.45	19.45
4.	Tensile Strength (kgf/15 mm width)	Outer Ply	D1: 5.76 D2: 5.63	D1: 6.37 D2: 5.11	D1: 5.37 D2: 3.07	D1: 6.08 D2: 2.81
		2nd Ply	D1: 6.47 D2: 6.03	D1: 6.50 D2: 2.92	D1: 6.69 D2: 3.36	D1: 6.67 D2: 5.86
		3rd Ply	D1: 6.37 D2: 6.22	D1: 6.91 D2: 2.94	D1: 7.50 D2: 3.66	D1: 7.68 D2: 6.12
		Inner Ply	D1: 8.73 D2: 8.34	D1: 6.51 D2: 5.11	D1: 7.81 D2: 6.80	D1: 8.15 D2: 6.61
5.	Oxygen Transmission Rate (cc/m^2 for 24 hours)	-	31.02	62.32	77942	81377
6.	Water Vapour Transmission Rate (g/m^2 for 24 hours)	-	0.908	3.486	10.40	10.50

D1: Direction 1; D2: Direction 2

(refer to Tables 1, 2, and 3). To test the shelf life of the mustard, 200 g samples were placed in nine different packaging materials and stored under accelerated conditions of 38 ± 5°C and 90 ± 2% RH using a Newtronic Walk-In Humidity Chamber. Samples were drawn and analysed every 15 days for the first 90 days, and subsequently at 7-day intervals until either 190 days or spoilage occurred, whichever came first. Each test was replicated three times throughout the six-month storage period [7,8,9].

The mustard was evaluated for its initial moisture content (IMC) and compared with the critical moisture content (CMC) set by FSSAI regulations (see Fig. 1). The moisture content of the mustard samples was measured using the vacuum oven drying method. Approximately 5 grams of the sample were placed in a dry dish and transferred to a vacuum oven, where it was dried at 103 ± 2°C under a pressure of 25 mm Hg for 5 hours. After drying, the sample was cooled in a desiccator and weighed, following the AOAC method [10] 2003. The water activity of the mustard was measured using an Aqualab 4TEV Water Activity Meter [11]. Other visual observations were recorded at each sample withdrawal throughout the exposure period which included assessments of colour, aroma, visual appearance, and microbial growth. The packaging materials were also inspected for any changes, such as colour alterations, cracks, discoloration, or delamination. Samples showing signs of microbial deterioration earlier than expected were removed from the study, and further investigations of those packaging materials were ceased. The transport worthiness test was performed to evaluate the hazards and performance of bulk packages during transit, including both drop tests and vibration tests. For the drop test, each sack was dropped three times from a height of 1.2 meters: first flat on one face, then on one edge, and finally on the bottom [12]. In the vibration test, the packed spice was placed on a vibration table and subjected to one hour of vibration at 120 cycles per minute and an amplitude of 2.54 cm [13]. All physico-chemical parameters were measured in triplicate, with significance determined at a 5% level ($p<0.05$).

3. RESULTS AND DISCUSSION

3.1 Moisture Content

Table 4 illustrates the impact of nine different packaging materials on the moisture content of mustard over 190 days of storage under accelerated conditions. Once the product exceeded the critical moisture level, it showed a significant texture change, becoming lumpy and unsaleable. As a hygroscopic substance, mustard absorbs moisture from the atmosphere. The highest average moisture content, 15.80%, was observed in mustard stored in PP Woven Bags without Liners. Caking or clumping of spices during handling, packaging, and storage is a common issue. Maintaining a low moisture content is crucial for ensuring the quality and shelf life of dried foods such as spices. Exposure to high humidity levels increases moisture content, which in turn raises water activity (a_w). This can accelerate various undesirable changes, including reduced dispersibility of the spice and increased mould growth. Preventing or controlling product moisture gain requires careful package design, including the selection of appropriate package dimensions and water vapor barrier materials [14,15,16]. These results indicate that moisture gain may be due to the hygroscopic nature of the dried product, the storage environment (such as temperature and relative humidity), and the inferior water vapour barrier properties of the packaging materials [17].

3.2 Water Activity

Table 5 presents the water activity of mustard seeds during storage. The data show a continuous increase in water activity throughout the storage period. The initial water activity was 0.4427, which was not conducive to microbial growth. However, water activity increased in all packaging materials used for the mustard. Under the specified storage conditions of temperature and humidity, the rate at which moisture transfers into packaged low-moisture spice, ultimately affecting shelf life depends on the food's water activity (a_w) and the water vapor permeability of the packaging materials. The liners demonstrated superior performance by allowing minimal water activity uptake compared to multiwall bags. The increase in water activity over the storage period may be attributed to moisture content changes caused by variations in temperature and relative humidity. These findings align with previous research by Mutungi et al. [18], Kumari et al. [19], and Kumari and Shrivastava [20].

3.3 Colour, Aroma Changes and Microbial Growth

Variations in color, aroma, and microbial growth were observed across all packaging materials during the exposure period, as summarized in Tables 6, 7, and 8. Among the packaging types, the PP Woven Bag with Liners showed no changes in color or aroma by the end of the storage period. In contrast, samples stored in multiwall paper bags exhibited whitish discoloration that progressed to a yellowish hue over time. The aroma of the spice in the PP Woven Bag without Liner and all multiwall paper bags shifted from a mushy odor to an unpleasant smell during storage. Fungal growth was detected in the P1 and the multiwall paper bag without lamination starting from the 146th and 111th days, respectively, and it later appeared in other multiwall paper bags throughout the storage period (Fig. 2). No signs of softening, cracking, or delamination were observed in any of the packaging materials. Microbial growth in foods is primarily facilitated by the presence of moisture. However, because dry foods like spices are hygroscopic and their moisture content can vary, the relative humidity in the storage environment plays a crucial role. When the balance between relative humidity and moisture content is disrupted, it creates an environment conducive to mold growth [21,22].

3.4 Shelf Life of Mustard

According to the moisture content results shown in Table 9, the longest shelf life recorded was 535 days for the PP Woven Bag with Liner IV (PA/EVOH/PE – 9 Ply; 70-80 µ) and 525 days for the PP Woven Bag with Liner III (PE/EVOH/PE – 9 Ply; 70-80 µ) under accelerated conditions. This was followed by a shelf life of 520 days for the PP Woven Bag with Liner II (PA/EVOH/PE – 5 Ply; 50-60 µ) and 510 days for the PP Woven Bag with Liner I (PE/EVOH/PE – 5 Ply; 50-60 µ). The Multiwall Paper Bag (Aluminium foil) achieved a shelf life of 405 days. The extended shelf life of products is largely due to the structure of the liners used as a packaging material. The spice industry currently uses liners made from either LDPE or LLDPE. To maintain the quality of spices, it is crucial that these liners possess oxygen and gas barrier properties to preserve their aroma. Therefore, choosing the right liner is a critical step. To address this, we have introduced novel liner combinations to evaluate their effectiveness in extending the shelf life of mustard. The longest shelf life was observed with the PA/EVOH/PE and PE/EVOH/PE combinations at various thicknesses. Polyethylene (PE) is a dominant material in the packaging industry due to its unique properties. The combination of high moisture resistance, excellent heat sealability at low temperatures, and strong tear resistance makes polyethylene a preferred choice and its adaptability along with cost-effectiveness further solidifies its position as a leading material for diverse packaging needs. Ethylene–vinyl alcohol copolymer (EVOH) is known for its excellent oxygen barrier properties. Ethylene contributes hydrophobic and olefinic characteristics, while the hydroxyl groups offer hydrophilic properties [23]. Due to hydrophilicity, EVOH's performance can be compromised by humidity, if it is directly exposed to the environment [24]. To enhance its moisture barrier properties, EVOH is often combined as a sandwich layer with other polymers like polypropylene (PP) and polyethylene (PE) through coextrusion [25]. Packaging materials incorporating EVOH exhibit high mechanical resistance to stretching and puncturing and offer lower gas permeability compared to other films [26,27]. PA is an engineering polymer recognized for its excellent chemical resistance, gas barrier properties, aroma retention, puncture strength, and bursting strength. This is why, in the outermost layer to observe the effect of higher performance material, PE is being replaced with PA to achieve improved mechanical and gas barrier properties. On the other hand, aluminium foil offers outstanding barrier properties that extend shelf life and protect contents from external factors. However, its drawbacks such as deadfold issues, pinholes, and limited tear strength can lead to reduced effectiveness. These defects may compromise the barrier integrity over time specifically in bulk packaging and in turn, reduce shelf life [28,29]. In our study, the performance of multiwall paper bags (MET PET and aluminium foil) was found to be inferior compared to polypropylene (PP) woven bags with liners. This is due to the lack of airtightness in the multiwall paper bags, which feature a valve or snout for filling, followed by folding and securing with pressure-sensitive tape. This design in addition to pinholes and deadfolds allows for gas permeation, rendering the high barrier properties of MET PET and aluminium foil less effective in providing adequate protection, ultimately resulting in reduced shelf life. To enhance the effectiveness of multiwall paper bags, a redesign focusing on improving airtightness is necessary; such modifications could potentially lead to better shelf life based on design efficiency. The integration of PA, EVOH, and PE in the liner structure represents a promising approach to sustainable packaging solutions in terms of recyclability and superior performance characteristics.

Table 4. Moisture Content of Mustard during storage in different packaging materials

P.M	Moisture Content (%)																				
	Days in Storage																				
	0	15	30	45	60	75	90	97	104	111	118	125	132	139	146	153	160	167	174	181	190
P1	6.72	6.93	8.25	10.62	10.82	11.47	11.61	12.05	12.21	12.31	12.47	12.74	12.95	15.80	D	D	D	D	D	D	D
P2	6.72	6.87	7.02	7.12	7.16	7.21	7.42	7.47	7.48	7.72	7.91	7.94	8.16	8.30	8.34	8.58	8.80	9.54	10.31	11.21	13.65
P3	6.72	6.75	6.77	6.82	7.09	7.24	7.39	7.54	7.56	7.60	7.61	7.62	7.65	7.69	7.89	8.13	8.16	8.38	10.04	10.83	13.33
P4	6.72	6.82	6.97	7.12	7.23	7.38	7.42	7.52	8.01	8.04	8.08	8.29	8.36	8.64	8.90	9.16	9.20	9.28	9.80	11.15	13.35
P5	6.72	6.80	6.95	7.10	7.25	7.40	7.55	7.67	7.83	8.02	8.10	8.17	8.19	8.27	8.33	8.48	8.64	8.93	9.18	10.67	12.47
P6	6.72	7.27	8.33	8.94	9.22	9.75	9.83	10.52	10.72	11.07	12.01	12.82	12.88	D	D	D	D	D	D	D	D
P7	6.72	6.77	6.98	7.18	7.63	7.79	8.03	8.14	8.46	8.57	8.59	9.25	9.65	10.34	D	D	D	D	D	D	D
P8	6.72	8.30	8.98	9.04	9.79	10.53	10.95	11.43	12.22	13.37	14.72	D	D	D	D	D	D	D	D	D	D
P9	6.72	8.32	9.29	10.28	10.56	11.14	11.41	11.71	12.88	D	D	D	D	D	D	D	D	D	D	D	D

P.M- Packaging Materials

[P1: PP woven Bag without Liner; P2: PP woven Bag with Liner I (PE/EVOH/PE – 5 Ply; 50-60 µ); P3: PP woven Bag with Liner II (PA/EVOH/PE – 5 Ply; 50-60 µ); P4: PP woven Bag with Liner III (PE/EVOH/PE – 9 Ply; 70- 80 µ); P5: PP woven Bag with Liner IV (PA/EVOH/PE – 9 Ply; 70- 80 µ); P6: Multiwall Paper Bag (MET PET); P7: Multiwall Paper Bag (Aluminium foil); P8: Multiwall Paper Bag (with Lamination); P9: Multiwall Paper Bag – Control]

D: Discontinued due to microbial growth

Table 5. Water Activity of Mustard during storage in different packaging materials

P.M	Water Activity																				
	Days in Storage																				
	0	15	30	45	60	75	90	97	104	111	118	125	132	139	146	153	160	167	174	181	190
P1	0.4427	0.4449	0.4469	0.4481	0.4539	0.4571	0.4682	0.4797	0.4993	0.5481	0.5619	0.5973	0.6134	0.6473	D	D	D	D	D	D	D
P2	0.4427	0.4449	0.4457	0.4479	0.4534	0.4644	0.4723	0.4896	0.5196	0.5289	0.5317	0.5345	0.5361	0.5393	0.5411	0.5425	0.5447	0.5469	0.5490	0.5511	0.5536
P3	0.4427	0.4448	0.4491	0.4517	0.4588	0.4624	0.4678	0.4716	0.4800	0.4971	0.5031	0.5065	0.5088	0.5107	0.5144	0.5173	0.5221	0.5257	0.5298	0.5324	0.5354
P4	0.4427	0.4445	0.4456	0.4465	0.4497	0.4513	0.4601	0.4693	0.4741	0.4801	0.4976	0.5011	0.5039	0.5055	0.5086	0.5118	0.5167	0.5193	0.5221	0.5248	0.5357
P5	0.4427	0.4431	0.4448	0.4489	0.4512	0.4523	0.4551	0.4566	0.4582	0.4599	0.4623	0.4647	0.4675	0.4692	0.4706	0.4731	0.4785	0.4961	0.5078	0.5123	0.5241
P6	0.4427	0.4486	0.4493	0.4603	0.4872	0.5063	0.5321	0.5379	0.5531	0.5748	0.5935	0.6153	0.6381	D	D	D	D	D	D	D	D
P7	0.4427	0.4435	0.4448	0.4459	0.4474	0.4498	0.4523	0.4547	0.4578	0.4619	0.4657	0.4738	0.4896	0.6364	D	D	D	D	D	D	D
P8	0.4427	0.4491	0.4517	0.4683	0.4925	0.5145	0.5496	0.5738	0.5963	0.6174	0.6489	D	D	D	D	D	D	D	D	D	D
P9	0.4427	0.4536	0.4603	0.4787	0.5167	0.5551	0.5845	0.6023	0.6596	D	D	D	D	D	D	D	D	D	D	D	D

P.M- Packaging Materials

[P1: PP woven Bag without Liner; P2: PP woven Bag with Liner I (PE/EVOH/PE – 5 Ply; 50-60 µ); P3: PP woven Bag with Liner II (PA/EVOH/PE – 5 Ply; 50-60 µ); P4: PP woven Bag with Liner III (PE/EVOH/PE – 9 Ply; 70- 80 µ); P5: PP woven Bag with Liner IV (PA/EVOH/PE – 9 Ply; 70- 80 µ); P6: Multiwall Paper Bag (MET PET); P7: Multiwall Paper Bag (Aluminium foil); P8: Multiwall Paper Bag (with Lamination); P9: Multiwall Paper Bag – Control]

D: Discontinued due to microbial growth

Table 6. Colour changes in Mustard during storage in different packaging materials

P.M	Colour changes																			
	Days in Storage																			
	15	30	45	60	75	90	97	104	111	118	125	132	139	146	153	160	167	174	181	190
P1	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	WD	WD	WD	YD	YD	YD
P2	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
P3	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
P4	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
P5	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
P6	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	WD	WD	WD	WD	WD	WD	WD	YD
P7	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	WD	WD	WD	WD	WD	YD	YD
P8	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	WD	WD	WD	WD	WD	WD	YD	YD	YD
P9	NC	NC	NC	NC	NC	NC	NC	NC	WD	WD	WD	WD	WD	WD	WD	WD	WD	YD	YD	YD

P.M- Packaging Materials

[P1: PP woven Bag without Liner; P2: PP woven Bag with Liner I (PE/EVOH/PE – 5 Ply; 50-60 µ); P3: PP woven Bag with Liner II (PA/EVOH/PE – 5 Ply; 50-60 µ); P4: PP woven Bag with Liner III (PE/EVOH/PE – 9 Ply; 70- 80 µ); P5: PP woven Bag with Liner IV (PA/EVOH/PE – 9 Ply; 70- 80 µ); P6: Multiwall Paper Bag (MET PET); P7: Multiwall Paper Bag (Aluminium foil); P8: Multiwall Paper Bag (with Lamination); P9: Multiwall Paper Bag – Control]

NC- No change

WD- Whitish discoloration

YD- Yellowish discoloration

Table 7. Aroma changes in Mustard during storage in different packaging materials

P.M	Aroma changes																			
	Days in Storage																			
	15	30	45	60	75	90	97	104	111	118	125	132	139	146	153	160	167	174	181	190
P1	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	MO	MO	MO	MO	BO	BO	BO
P2	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
P3	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
P4	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
P5	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
P6	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	MO	MO	MO	MO	MO	BO	BO	BO
P7	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	MO	MO	MO	MO	MO	BO	BO
P8	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	MO	MO	MO	MO	MO	MO	MO	BO	BO	BO
P9	NC	NC	NC	NC	NC	NC	NC	NC	MO	MO	MO	MO	MO	BO	BO	BO	BO	BO	BO	BO

P.M- Packaging Materials

[P1: PP woven Bag without Liner; P2: PP woven Bag with Liner I (PE/EVOH/PE – 5 Ply; 50-60 µ); P3: PP woven Bag with Liner II (PA/EVOH/PE – 5 Ply; 50-60 µ); P4: PP woven Bag with Liner III (PE/EVOH/PE – 9 Ply; 70- 80 µ); P5: PP woven Bag with Liner IV (PA/EVOH/PE – 9 Ply; 70- 80 µ); P6: Multiwall Paper Bag (MET PET); P7: Multiwall Paper Bag (Aluminium foil); P8: Multiwall Paper Bag (with Lamination); P9: Multiwall Paper Bag – Control]

NC- No change

MO- Mushy odour

BO- Bad odour

Table 8. Microbial growth in Mustard during storage in different packaging materials

P.M	Microbial Growth																			
	Days in Storage																			
	15	30	45	60	75	90	97	104	111	118	125	132	139	146	153	160	167	174	181	190
P1	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	FG	FG	FG	FG	FG	FG	FG
P2	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG
P3	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG
P4	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG
P5	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG
P6	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	FG	FG	FG	FG	FG	FG	FG	FG
P7	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	FG	FG	FG	FG	FG	FG	FG
P8	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	FG	FG	FG	FG	FG	FG	FG	FG	FG	FG
P9	NG	NG	NG	NG	NG	NG	NG	NG	FG	FG	FG	FG	FG	FG	FG	FG	FG	FG	FG	FG

P.M- Packaging Materials

[P1: PP woven Bag without Liner; P2: PP woven Bag with Liner I (PE/EVOH/PE – 5 Ply; 50-60 µ); P3: PP woven Bag with Liner II (PA/EVOH/PE – 5 Ply; 50-60 µ); P4: PP woven Bag with Liner III (PE/EVOH/PE – 9 Ply; 70- 80 µ); P5: PP woven Bag with Liner IV (PA/EVOH/PE – 9 Ply; 70- 80 µ); P6: Multiwall Paper Bag (MET PET); P7: Multiwall Paper Bag (Aluminium foil); P8: Multiwall Paper Bag (with Lamination); P9: Multiwall Paper Bag – Control]

NG- No growth

FG- Fungus growth

Table 9. Shelf Life of Mustard

Packaging Materials	Shelf Life in Days at 38 ± 1ºC & 90 ± 2 % R. H.	Expected Shelf Life in Days at 27 ± 2ºC & 65 ± 2 % R. H
P1	40 days	120 days
P2	170 days	Up to 510 days
P3	173 days	Up to 520 days
P4	175 days	Up to 525 days
P5	178 days	Up to 535 days
P6	92 days	Up to 275 days
P7	135 days	Up to 405 days
P8	60 days	Up to 180 days
P9	40 days	Up to 120 days

P.M- Packaging Materials

[P1: PP woven Bag without Liner; P2: PP woven Bag with Liner I (PE/EVOH/PE – 5 Ply; 50-60 µ); P3: PP woven Bag with Liner II (PA/EVOH/PE – 5 Ply; 50-60 µ); P4: PP woven Bag with Liner III (PE/EVOH/PE – 9 Ply; 70- 80 µ); P5: PP woven Bag with Liner IV (PA/EVOH/PE – 9 Ply; 70- 80 µ); P6: Multiwall Paper Bag (MET PET); P7: Multiwall Paper Bag (Aluminium foil); P8: Multiwall Paper Bag (with Lamination); P9: Multiwall Paper Bag – Control]

Table 10. Evaluation of Bulk Pack of Mustard for Transport Worthiness Trials

Packaging Materials	Vibration test		Drop test	
	External	Internal	External	Internal
P1	No damage	No damage	No damage	No damage
P2	No damage	No damage	No damage	No damage
P3	No damage	No damage	No damage	No damage
P4	No damage	No damage	No damage	No damage
P5	No damage	No damage	No damage	No damage
P6	No damage	No damage	No damage	No damage
P7	No damage	No damage	No damage	No damage
P8	No damage	No damage	No damage	No damage
P9	No damage	No damage	No damage	No damage

P.M- Packaging Materials

[P1: PP woven Bag without Liner; P2: PP woven Bag with Liner I (PE/EVOH/PE – 5 Ply; 50-60 µ); P3: PP woven Bag with Liner II (PA/EVOH/PE – 5 Ply; 50-60 µ); P4: PP woven Bag with Liner III (PE/EVOH/PE – 9 Ply; 70- 80 µ); P5: PP woven Bag with Liner IV (PA/EVOH/PE – 9 Ply; 70- 80 µ); P6: Multiwall Paper Bag (MET PET); P7: Multiwall Paper Bag (Aluminium foil); P8: Multiwall Paper Bag (with Lamination); P9: Multiwall Paper Bag – Control]

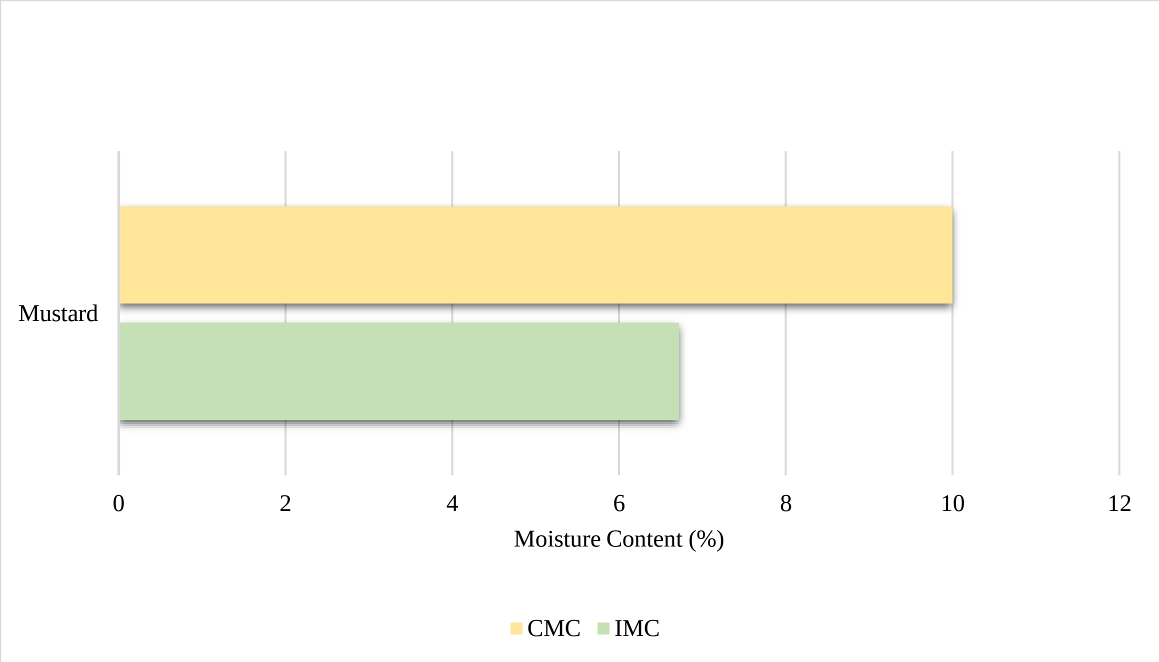

Fig. 1. Initial Moisture Content (IMC) and Critical Moisture Content (CMC) of Mustard

Best results were observed in PP woven Bag with Liner IV (PA/EVOH/PE – 9 Ply; 70-80 μ)

Microbial growth was observed on Multiwall paper bag

Fig. 2. Microbial growth during storage

3.5 Evaluation of Bulk Pack of Mustard for Transport Worthiness Trials

To assess the transport readiness of the nine selected packaging materials, drop and vibration tests were carried out. None of the packages showed any rupture or leakage of the mustard seeds. Packaging is essential for safeguarding products against various transportation challenges, and the transport worthiness tests help predict the stability of the packaging during transit. A summary of the results from the vibration and drop tests conducted on the nine packaging options is provided in Table 10.

4. CONCLUSION

Based on the comprehensive analysis, transport worthiness tests, and shelf life across nine different packaging options; PP woven Bag with Liners were found to be particularly effective. The effectiveness of the packaging materials is attributed to the ability of the liners used to manage moisture content and water activity, resist microbial deterioration and extended the shelf life of the product. Hence, the recommended packaging options are PP woven Bag with Liner IV (PA/EVOH/PE – 9 Ply; 70- 80 µ), PP woven Bag with Liner III (PE/EVOH/PE – 9 Ply; 70- 80 µ), PP woven Bag with Liner II (PA/EVOH/PE – 5 Ply; 50-60 µ) and PP woven Bag with Liner I (PE/EVOH/PE – 5 Ply; 50-60 µ). However, for logistics and a shelf life of up to one-year, multiwall paper bags with aluminium foil also proved effective and may be utilized. While metalized and aluminium foil-based multiwall paper bags are intended to provide optimal shelf life, design limitations have resulted in poorer performance than anticipated. The extended shelf life of the spice is significantly influenced by the structure of the liners, which should possess effective oxygen and gas barrier properties to preserve the aroma, critical for quality. Hence, utilizing advanced and sustainable combinations like PA/EVOH/PE and PE/EVOH/PE can significantly enhance barrier properties compared to traditional LDPE or LLDPE options and provide an extended shelf life.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. India Brand Equity Foundation (IBEF). Spices industry and export in India; 2024. Available:https://www.ibef.org/exports/spice-industry-india
2. Spices Board's Trade Information Services. Review of export performance of spices during 2023-24; 2024. Available:https://www.indianspices.com/box2info.html
3. Rahman M, Khatun A, Liu L, Barkla BJ. Brassicaceae mustards: phytochemical constituents, pharmacological effects, and mechanisms of action against human disease. Int J Mol Sci. 2024;25(16):9039. Available:https://doi.org/10.3390/ijms25169039
4. Shankar S, Segaran G, Sundar Dhevi VR, Settu S, Sathiavelu M. Brassicaceae - a classical review on its pharmacological activities. Int J Pharm Sci Rev Res. 2019;55(1):107-113.
5. Anandakumar S, Visvanathan R. Packaging and storage of spices. In: Ravindran PN, Sivaraman K, Devasahayam S, Babu KN, editors. Handbook of spices in India: 75 years of research and development. Singapore: Springer. 2024;68. Available:https://doi.org/10.1007/978-981-19-3728-6_68
6. Ammaan M, Panjavarnam G, Sudha R, Anuradha P. An overview of packaging technologies for seed spices: a review. Plant Arch. 2024;24(2):725-730.
7. Duarte S, Betoret E, Betoret N. Shelf life and functional quality of almond bagasse powders as influenced by dehydration and storing conditions. Foods. 2024;13(5):744. DOI: 10.3390/foods13050744
8. Macedo ISM, Sousa-Gallagher MJ, Oliveira JC, Byrne EP. Quality by design for packaging of granola breakfast product. Food Control. 2013;29(2):438-443.
9. AOAC. Official methods of analysis of the AOAC International. 17th ed. Washington, DC: Association of Official Analytical Chemists; 2003.
10. Carolina H, Andrés C, Mariane L, Jorge S. Storage stability test of apple peel powder using two packaging materials: high-density polyethylene and metalized films of high barrier. Ind Crops Prod. 2013;45:121-127. Available:https://doi.org/10.1016/j.indcrop.2012.11.032
11. Chien HI, Yen YF, Lee YC, Wei PC, Huang CY, Tseng CH, Yen FL, Tsai YH. Determination of the bacterial community

of mustard pickle products and their microbial and chemical qualities. Biology (Basel). 2023;12(2):258.
DOI: 10.3390/biology12020258

12. IS 7028-4. Performance tests for complete, filled transport packages, Part 4: vertical impact drop test [TED 24: Transport packages]. New Delhi: Bureau of Indian Standards. 1987;2-8.
13. IS 7028-2. Performance tests for complete, filled transport packages, Part 2: vibration test at fixed low frequency [TED 24: Transport packages]. New Delhi: Bureau of Indian Standards. 2002;1-3.
14. Abdissa B, Math R, Desham K, Korra S. Moisture sorption behavior and shelf life prediction of teff seed and flour. J Appl Packag Res. 2020;12(1)1.
15. Pushpadass HA, Emerald FME, Rao KJ, Nath BS, Chaturvedi B. Prediction of shelf life of Gulab jamun mix using simulation and mathematical modeling – based on moisture gain. J Food Process Preserv. 2014;38(4):1517-1526.
Available:https://doi.org/10.1111/jfpp.12111
16. Saha D, Nanda SK, Yadav DN. Shelf-life study of spray-dried groundnut milk powder. J Food Process Eng. 2020;43(3).
Available:https://doi.org/10.1111/jfpe.13259
17. Alfiya PV, Jayashree E, Sneha C. Development and shelf-life evaluation of spice flavoured sorghum (*Sorghum bicolor*) cookies: a study on valorisation of millets for food security. The Pharma Innovation J. 2023;SP-12(12):96-112.
18. Mutungi CM. Storage of mung bean and pigeon pea grains in hermetic triple-layer bags stops losses caused by *Callosobruchus maculatus*. J Stored Prod Res. 2014;58:39-47.
19. Kumari A, Rajak D, Kumar V. Comparative study on storage behavior of food grain in different storage bags. B.Tech project report submitted to College of Agricultural Engineering, RAU, Pusa, Bihar; 2015.
20. Kumari A, Shrivastava M. Effect of storage duration on water activity of green gram stored in hermetic and other bags. Int J Curr Microbiol App Sci. 2018;7(7):733-740.
Available:https://doi.org/10.20546/ijcmas.2018.707.090
21. Zhang M. In: Mujumdar AS, editor. Microbiology and safety of dried vegetables. New York: Taylor & Francis; 2017.
22. Beuchat LR, Komitopoulou E, Beckers H, Betts RP, Bourdichon F, Fanning S, Ter Kuile BH. Low-water activity foods: increased concern as vehicles of foodborne pathogens. J Food Prot. 2013;76(1):150-172.
DOI: 10.4315/0362-028X.JFP-12-211
23. Mateo EM, Gómez JV, Domínguez I, Gimeno-Adelantado JV, Mateo-Castro R, Gavara R, Jiménez M. Impact of bioactive packaging systems based on EVOH films and essential oils in the control of aflatoxigenic fungi and aflatoxin production in maize. Int J Food Microbiol. 2017;254:36-46.
24. Gavara R, Catalá R, Carballo GL, Cerisuelo JP, Dominguez I, Muriel-Galet V, Hernandez-Muñoz P. Use of EVOH for food packaging applications. In: Reference Module in Food Science. Elsevier. 2016;1-6.
25. Wu J-H, Wu C-P, Kuo MC, Tsai Y. Characterization and properties of reactive poly (lactic acid)/ethylene–vinyl alcohol copolymer blends with chain-extender. J Polym Environ. 2016;40:1204-1214.
26. Gao S, Hanson BD, Qin R, Wang D, Yates SR. Comparisons of soil surface sealing methods to reduce fumigant emission loss. J Environ Qual. 2011;40(5):1480-1487.
27. Arvanitoyannis IS, Stratakos AC. Application of modified atmosphere packaging and active/smart technologies to red meat and poultry: a review. Food Bioprocess Technol. 2012;5(5):1423-1446.
28. Giovanelli G, Limbo S, Buratti S. Effects of new packaging solutions on physico-chemical, nutritional and aromatic characteristics of red raspberries (*Rubus idaeus*) in postharvest storage. Postharvest Biol Technol. 2014;98:72-81.

29. Gantner M, Król K, Kopczyńska K. Application of MAP and ethylene–vinyl alcohol copolymer (EVOH) to extend the shelf-life of green and white asparagus (*Asparagus officinalis*) spears. Food Meas. 2020;14:2030-2039. Available:https://doi.org/10.1007/s11694-020-00449-6

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