ISSN: 2754-477X

Journal of Food Technology & Nutrition Sciences

Research Article

Open Access

Sustainable Packaging Solutions for Bulk Export of Cumin Seeds to Global Spice Markets

Badal Dewangan* and Donal Bhattacharjee

R&D and Consultancy Department, Indian Institute of Packaging, Mumbai, Maharashtra, India

ABSTRACT

The objective of this study was to determine the most effective bulk packaging materials for cumin seeds, ensuring the preservation of quality during export processes. Preserving the quality of spices is of paramount importance, particularly with regard to utilizing effective oxygen and gas barriers to maintain aroma. To address these concerns, multiwall paper bags were tested for their efficacy in prolonging the shelf life of cumin seeds. A selection of four packaging materials, chosen based on sustainability criteria, was exposed to accelerated aging conditions set at 38±1°C and 90±2% relative humidity over a period of six months, and shelf life was evaluated. Export packaging specifications were developed using paper-based sustainable packaging materials to ensure compliance with transport requirements. The results demonstrated that multiwall paper bags lined with aluminium foil successfully inhibited moisture and oxygen ingress, thereby preserving the quality of the product and extending its shelf life. Although fossil-based packaging is better suited for long-distance transport, multilayer paper bags offer unique advantages. They meet essential requirements and are inherently sustainable, allowing producers to support sustainability and a circular economy.

***Corresponding author**

Badal Dewangan, R&D and Consultancy Department, Indian Institute of Packaging, Mumbai, Maharashtra, India.

Received: April 02, 2025; **Accepted:** April 07, 2025; **Published:** April 15, 2025

Keywords: Cumin Seed, Packaging, Shelf Life, Sustainable, Bulk

Introduction

Packaging is essential in preserving the safety and quality of food items as they traverse the supply chain. It serves to protect food from harmful external factors, including mechanical impacts, light exposure, and moisture, thereby ensuring the integrity and longevity of the products. The selection of packaging materials, design, and strategies can vary significantly, influencing not only the effectiveness of the packaging but also its environmental impact. Sustainable packaging is increasingly recognized as a critical component of food packaging strategies. It is characterized by its effectiveness, efficiency, and safety for both human health and ecological systems [1-3]. As the global population continues to grow and supply chains become more complex, the demand for packaging is consistently rising [4]. According to Smithers Pira's report (2024) "The Future of Global Packaging to 2028," the global packaging market is projected to expand significantly, from $1.17 trillion in 2023 to $1.42 trillion by 2028 [5]. This growth is driven by increasing consumer demand, a rising global population, and the booming e-commerce sector. However, a major concern arises from post-consumer packaging waste, particularly with single-use and multilayer materials that contribute to environmental challenges. In the food industry, common packaging materials include petroleum-based, non-biodegradable polymers such as polyethylene and polypropylene, which are widely used for single-use plastic bags, wraps, and inserts [6,7]. While synthetic plastic packaging offers several advantages—such as affordability, lightweight design, flexibility, transparency, and impermeability—it also poses significant environmental risks if not managed properly. Thus, there is an urgent need for innovative approaches to sustainable packaging that can mitigate these risks while still meeting the demands of a growing market.

Cumin (*Cuminum cyminum* L.), known as "Jeera" in India, is a significant seed spice derived from an annual herb cultivated globally. It belongs to the Apiaceae family and originated in the Levant, Upper Egypt, and the Mediterranean region. Cumin has been utilized as a spice since ancient times and is a key ingredient in various mixed spices, chutneys, and curry powders. In the Middle East, it is commonly used to enhance the flavour of meats and vegetables, while in Europe, it enjoys similar popularity. India stands as the largest producer and consumer of cumin worldwide. Cumin seeds hold significant culinary and industrial importance. They are utilized in traditional culinary practices, where they are added to dishes such as rice, bread, biscuits, and beverages like lassi. Furthermore, cumin is fried or incorporated into various recipes to enhance flavour. In addition to its culinary uses, the volatile oil and oleoresin extracted from cumin serve crucial roles in both the food flavouring industry and the cosmetics and perfumery sectors. Specifically, cumin seeds and cumin oil are employed to impart flavour to soups, meats, cheese, pickles, and bread products. The volatile oil from cumin is also employed as a fragrant component in the formulation of ointments, lotions, creams, and perfumes. Moreover, it is used in the food flavour processing industry to regulate the volatile oil content of oleoresins. Cumin is also noted for its medicinal applications, being used in the treatment of various ailments. Importantly, cumin seeds are recognized as an excellent source of iron [8-10]. In the 2023-24 season, India continues to be the largest producer, consumer, and exporter of cumin. The country accounts for approximately 70% of global cumin production, with Gujarat and

Rajasthan being the primary cultivation states, contributing over 95% of India's total output. This year, the area under cumin cultivation has significantly increased to about 12.5 lakh hectares, up from 7.14 lakh hectares in the previous year, resulting in an estimated production of 7.6 lakh tonnes, compared to 4.63 lakh tonnes in 2022-23. Gujarat is expected to produce a record 4.08 lakh tonnes, nearly double its output from last year [11,12].

Plastic waste in oceans is a critical global environmental issue, primarily due to packaging materials. In 2023, global plastic production reached 413.8 million metric tons, with packaging contributing to 40% of this waste. A large portion of plastic waste ends up in the ocean, with plastics making up at least 85% of marine litter, threatening ecosystems and wildlife. Sustainable packaging is now a key focus, guided by the "3Rs"—Reduce, Reuse, and Recycle. Paper-based packaging, particularly multiwall paper bags with metallization, aluminium foil, and wax coatings, offers an environmentally friendly alternative to plastics. These bags are made from renewable resources, are biodegradable, and provide enhanced protection from moisture, oxygen, and light. Multiwall paper bags not only extend product shelf life but also support sustainability efforts by reducing environmental impact. By adopting these innovative packaging solutions, businesses can protect their products while contributing to a circular economy and addressing the growing plastic waste crisis. Cumin seeds, being hygroscopic, necessitate packaging materials with excellent barrier properties to prevent moisture absorption and maintain quality. Currently, Indian cumin seed exporters primarily utilize bulk packaging without standardized technical specifications, which presents challenges in ensuring consistent quality and accurately assessing shelf life. To protect the quality of spices, it is essential to use high-barrier packaging materials that guard against oxidation and preserve freshness. The packaging industry in India is experiencing a significant shift towards sustainability, influenced by regulatory requirements, consumer preferences, and innovative practices. By adopting sustainable packaging designs, spice and packaging companies can minimize their environmental impact while enhancing their competitiveness in the global market. In response to the critical issues confronting the spice sector, the Indian Institute of Packaging (IIP) in Mumbai undertook an extensive investigation with the objective of devising efficient bulk packaging strategies. Funded by the Spices Board India under the Ministry of Commerce and Industry, this study aimed to generate effective packaging solutions for cumin seed through rigorous testing of sustainable packaging materials and evaluating their influence on shelf life, particularly for the export market.

Materials and Methods

The cumin seed was sourced from M/s Jabs International Private Limited, Navi Mumbai, while the multiwall paper (MWP) as specified by IIP were manufactured and obtained from M/s Paper Bag Mfg. Co., Mumbai. The packaging of the samples was carried out at the Research and Development Department laboratory of the Indian Institute of Packaging in Mumbai. A selection of multiwall paper bags was employed and the specific characteristics of these materials are as detailed below:

MWP1: Multiwall Paper Bag without coating/ lamination – Control
MWP2: Multiwall Paper Bag laminated with MET PET (Metallized PET)
MWP3: Multiwall Paper Bag laminated with Aluminium foil
MWP4: Multiwall Paper Bag with wax coating

Mechanical and Barrier Properties Testing

The packaging materials were evaluated for their physical, mechanical, and physico-chemical properties. Mechanical properties of PP woven bags, paper woven bags, and liners, including breaking load, elongation, seam strength, tensile strength, and strain, were tested using a universal testing machine (UTM) as per ASTM D882-18 standards [13]. The water vapor and oxygen transmission rates of the liners were measured following ASTM F1249 standards. Migration testing of the liners was conducted according to IS 9845-1998 guidelines [14].

Accelerated Shelf Life Study

To assess the shelf life of cumin, 200-gram samples were packaged in ten materials and exposed to accelerated aging conditions (38 ± 5°C, 90 ± 2% RH) in a Newtronic Walk-In Humidity Chamber. This simulated extreme conditions, allowing for faster evaluation of packaging durability. Samples were analyzed regularly, with testing every 15 days for the first 90 days and then at 7-day intervals until 190 days or spoilage occurred. Each test was performed in triplicate throughout the six-month period.

Moisture Content

The initial moisture content (IMC) of cumin seeds was measured and compared to the critical moisture content (CMC) as per FSSAI regulations (Figure 1). Moisture content was determined using the Ohaus MB27 moisture balance, following AOAC (2003) standards [15].

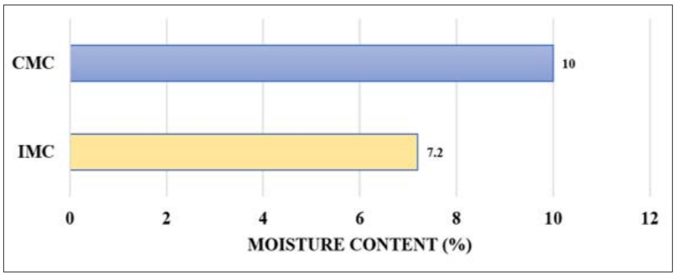


Figure 1: Initial Moisture Content (IMC) and Critical Moisture Content (CMC) of Cumin Seed

Water Activity

Water activity was measured using an Aqualab 4TEV Water Activity Meter. The sample was placed in a sealed disposable cup to achieve vapor equilibrium, and an infrared beam measured the dew point temperature, which was then used to calculate the water activity.

Visual Observations

Colour, aroma, appearance, and microbial growth were monitored throughout the exposure period. Packaging materials were checked for physical changes like colour shifts, cracks, or delamination. Samples showing signs of microbial spoilage were excluded from further analysis.

Transport Worthiness Test

Drop and vibration tests assessed packaging durability. Each sack was dropped three times from 1.2 meters onto different surfaces, and vibration tests were conducted for one hour at 120 cycles per minute with a 2.54 cm amplitude, following IS 7028-4 (1987) and IS 7028-2 (2002) standards [16,17].

Statistical Analysis

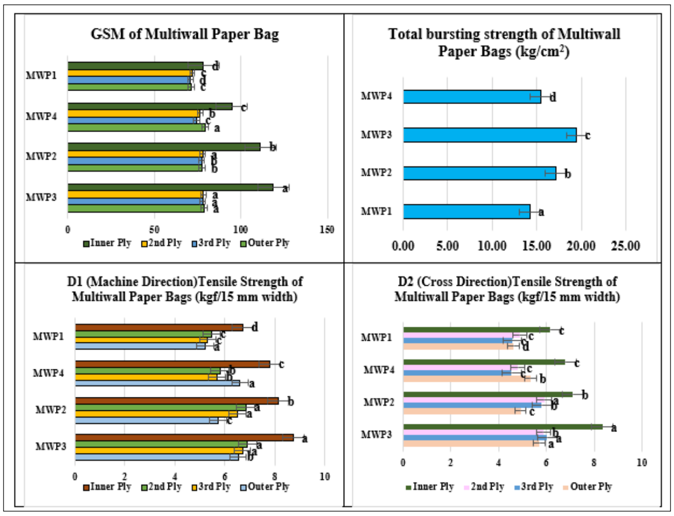
All physico-chemical parameters were measured in triplicate, with significance determined at a 5% level ($p<0.05$).

Results and Discussion

Mechanical Properties of Multiwall Paper Bags

The data presented in Figure 2 shows the total GSM and bursting strength (in kg/cm²) of various multiwall paper bags. Multiwall paper bags laminated with aluminium foil and MET PET exhibit the highest GSM, indicating they are the most durable options. In contrast, laminated and non-coated bags are lighter and less sturdy. The MWP3 (Multiwall Paper Bag laminated with Aluminium foil) has the highest bursting strength at 19.45 kg/cm², demonstrating that the aluminium foil layer enhances the bag's structural integrity and burst resistance. MWP2 (Multiwall Paper Bag laminated with MET PET) follows with a slightly lower bursting strength of 17.13 kg/cm², showing good durability. MWP4 (multiwall paper bag with wax coating) has a significant decrease in bursting strength to 15.45 kg/cm², providing moderate protection, but not as much as aluminium foil or MET PET. MWP1 (multiwall paper bag without coating/lamination) shows the lowest bursting strength at 14.2 kg/cm², likely due to the absence of additional protective layers. Overall, MWP3 stands out as the most robust option, making it the best choice for packaging cumin seeds. Choosing the right materials can enhance product safety and shelf life, benefiting both manufacturers and consumers.

Figure 2 also displays the tensile strength (in kgf/15 mm width) of multiwall paper bags in both the machine direction (D1) and cross direction (D2) for various bag types (aluminium foil, MET PET, wax coating, and no coating/lamination). In all bag types, the inner ply consistently shows the highest tensile strength in both directions. MWP3 has the highest tensile strength overall. Typically, tensile strength is higher in the machine direction (D1) than in the cross direction (D2), as paper fibers in multiwall bags are aligned more in the machine direction, offering better resistance to tensile forces. In the cross direction, tensile stress causes fiber separation, resulting in lower tensile strength.



(Means in the same alphabet do not differ significantly by Tukey test at 5%)

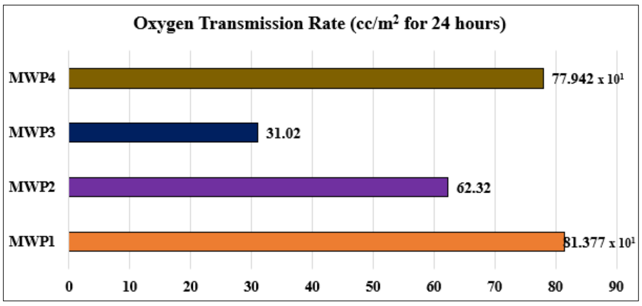
[**MWP1:** Multiwall Paper Bag without coating/ lamination – Control; **MWP2:** Multiwall Paper Bag laminated with MET PET; **MWP3:** Multiwall Paper Bag laminated with Aluminium foil; **MWP4:** Multiwall Paper Bag with wax coating]

Figure 2: Mechanical Properties of Multiwall Paper Bags

Barrier Properties of Multiwall Paper Bags

The data in Figures 3 and 4 compare the oxygen transmission rates (OTR) of various multiwall paper bags, highlighting significant differences in their ability to block oxygen. MWP3 (Multiwall Paper Bag laminated with Aluminium foil) exhibited the lowest OTR at 31.02 cc/m² over 24 hours, offering the best oxygen barrier, ideal for preserving oxygen-sensitive products like cumin seeds. MWP2 (Multiwall Paper Bag laminated with MET PET) showed a moderate OTR of 62.32 cc/m², while MWP4 (multiwall paper bag with wax coating) had a much higher OTR of 779.42 cc/m². MWP1 (uncoated/laminated) displayed the highest OTR at 813.77 cc/m², providing the weakest protection against oxygen. This highlights the superior oxygen barrier properties of MWP3, followed by MWP2, MWP4, and MWP1 in decreasing order of effectiveness.

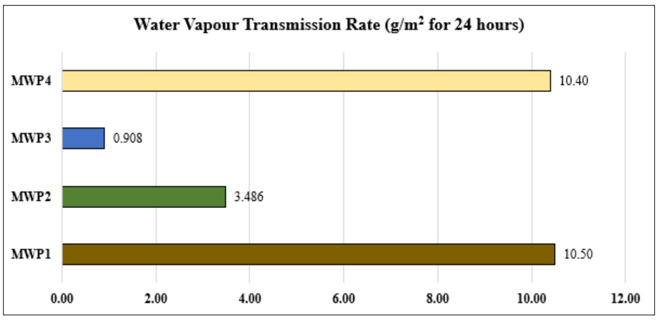
MWP3 also showed the lowest water vapor transmission rate (WVTR) of 0.908 g/m² over 24 hours, indicating it provides the strongest barrier against moisture. MWP2 had a WVTR of 3.486 g/m², still offering strong moisture resistance. In contrast, MWP4's WVTR was 10.40 g/m², and MWP1 had the highest at 10.50 g/m², indicating the weakest moisture barriers. These findings underscore the importance of selecting the right packaging material to preserve the quality and shelf life of cumin seeds.



[**MWP1:** Multiwall Paper Bag without coating/ lamination – Control; **MWP2:** Multiwall Paper Bag laminated with MET PET; **MWP3:** Multiwall Paper Bag laminated with Aluminium foil; **MWP4:** Multiwall Paper Bag with wax coating]

Note: The data for multiwall paper bags (MPB) without lamination and with wax coating are 813.77 and 779.42, respectively. However, for graphical representation, these values are expressed as 81.37 x 10¹ and 77.94 x 10¹.

Figure 3: Oxygen Transmission Rate of Multiwall Paper Bags



[**MWP1:** Multiwall Paper Bag without coating/ lamination – Control; **MWP2:** Multiwall Paper Bag laminated with MET PET; **MWP3:** Multiwall Paper Bag laminated with Aluminium foil; **MWP4:** Multiwall Paper Bag with wax coating]

Figure 4: Water Vapour Transmission Rate of Multiwall Paper Bags

Moisture Content

The analysis of the moisture content in fennel seeds (Table 1) during storage across four different packaging materials (MWP1: Multiwall Paper Bag without coating/ lamination – Control; MWP2: Multiwall Paper Bag laminated with MET PET; MWP3: Multiwall Paper Bag laminated with Aluminium foil; MWP4: Multiwall Paper Bag with wax coating) reveals significant on the effect of packaging for the moisture gain and the overall quality of the seed spice. The moisture content in cumin seeds stored in MWP1 began at 7.20% and steadily increased throughout the storage period. By day 30, it increased to 10.50%. Beyond day 139, the testing was discontinued due to microbial growth (indicated as "D" from day 139 to 190 as presented in Table 1). In MWP2 by day 60, the moisture content reached 10.20%, and by day 190, it had increased to 18.20%. In MWP3 by day 118, it reached 10.77%, slightly above the 10% threshold. The moisture content in MWP4 reached 9.99% on 45 days. Caking or clumping of spices is a prevalent challenge in the industry, occurring during both processing and storage. This phenomenon refers to the formation of persistent clumps due to the stickiness of spice particles, which can lead to reduced functionality and quality [18,19]. These findings indicate that moisture gain is influenced by several factors: the hygroscopic nature of dried products, environmental conditions such as temperature and relative humidity, and the properties of the packaging materials used [13].

Table 1: Moisture Content of Cumin Seed During Storage in Different Packaging Materials

Moisture Content (%)				
Days in Storage				
P.M	MWP1	MWP27	MWP3	MWP4
0	7.20	7.20	7.20	7.20
15	7.74	7.31	7.36	7.78
30	10.50	7.88	8.09	8.94
45	10.88	8.00	8.36	9.99
60	11.22	10.20	8.50	10.50
75	11.24	10.43	9.58	11.02
90	14.37	11.13	8.91	11.11
97	14.72	11.41	9.27	11.12
104	15.11	11.83	9.62	11.68
111	15.53	12.52	9.90	12.30
118	15.68	12.71	10.77	12.87
125	16.20	13.17	10.88	13.78
132	16.32	13.22	11.13	15.51
139	D	13.28	11.72	15.53
146	D	13.65	12.24	D
153	D	13.74	12.25	D
160	D	14.11	12.50	D
167	D	14.17	12.97	D
174	D	14.87	13.40	D
181	D	15.35	15.37	D
190	D	18.20	17.67	D

P.M- Packaging Materials

[**MWP1:** Multiwall Paper Bag without coating/ lamination – Control; **MWP2:** Multiwall Paper Bag laminated with MET PET; **MWP3**: Multiwall Paper Bag laminated with Aluminium foil; **MWP4**: Multiwall Paper Bag with wax coating]

D: Discontinued due to microbial growth

Water Activity

The water activity of cumin seeds (Table-2) stored in MWP1 (Multiwall Paper Bag without coating/lamination) started at 0.4418 on day 0 and gradually increased over time. By day 132, the water activity reached 0.6654, and measurements beyond this point were discontinued due to microbial growth (denoted as "D"). The water activity of cumin seeds stored in MWP2 (Multiwall Paper Bag laminated with MET PET) also increased gradually, reaching 0.6178 by day 190. Similarly, the water activity of cumin seeds stored in MWP3 (Multiwall Paper Bag laminated with Aluminium foil) increased to 0.6004 by day 190. The water activity of cumin seeds stored in MWP4 (multiwall paper bag with wax coating) increased as well, reaching 0.6500 by day 139, with further measurements discontinued due to microbial growth. MWP1 (Multiwall Paper Bag without coating/lamination) was the least effective in maintaining stable water activity. High water activity levels can significantly reduce the shelf life of food products, while lower values tend to extend it. Hygroscopic materials, such as cumin seeds, have the capacity to absorb water molecules from their environment. When relative humidity levels are high enough, these materials will take in moisture to equilibrate with the surrounding humidity, resulting in an increase in their overall water content [20]. The rise in water activity during storage correlates with an increase in moisture content, which escalated from an initial 7.20% to 16.32%. Similar observations were made by [21,22].

Table 2: Water Activity of Cumin Seed During Storage in Different Packaging Materials

Water Activity				
Days in Storage				
P.M	MWP1	MWP27	MWP3	MWP4
0	0.4418	0.4418	0.4418	0.4418
15	0.4578	0.4512	0.4493	0.4497
30	0.4773	0.4597	0.4521	0.4536
45	0.5143	0.4628	0.4589	0.4653
60	0.5366	0.4753	0.4603	0.4795
75	0.5638	0.4825	0.4651	0.5049
90	0.6033	0.4931	0.4761	0.5347
97	0.6221	0.4982	0.4835	0.5561
104	0.6213	0.5013	0.4911	0.5872
111	0.6364	0.5073	0.4978	0.6164
118	0.6401	0.5155	0.5037	0.6276
125	0.6523	0.5249	0.5163	0.6351
132	0.6654	0.5365	0.5246	0.6427
139	D	0.5478	0.5368	0.6500
146	D	0.5527	0.5423	D
153	D	0.5645	0.5571	D
160	D	0.5766	0.5648	D
167	D	0.5862	0.5768	D
174	D	0.5947	0.5836	D
181	D	0.6053	0.5957	D
190	D	0.6178	0.6004	D

P.M- Packaging Materials

[**MWP1:** Multiwall Paper Bag without coating/ lamination – Control; **MWP2:** Multiwall Paper Bag laminated with MET PET; **MWP3:** Multiwall Paper Bag laminated with Aluminium

foil; **MWP4:** Multiwall Paper Bag with wax coating]
D: Discontinued due to microbial growth

Colour, Aroma Changes and Microbial Growth

The results in Table 3 show the colour changes of cumin seeds across different packaging materials during the storage period. In MWP1 (Multiwall Paper Bag without coating/lamination), no colour change (NC) was observed up to 132 days, after which whitish discoloration (WD) began and continued throughout the storage. In MWP2 (Multiwall Paper Bag laminated with MET PET) and MWP3 (Multiwall Paper Bag laminated with Aluminium foil), no colour change (NC) was observed during the entire storage period. In MWP4 (multiwall paper bag with wax coating), no colour change was noted until day 139, after which whitish discoloration (WD) began. The discoloration in cumin seeds stored in various packaging materials reflects the interaction between moisture, light, and the packaging's effectiveness in protecting the seeds. The lack of discoloration in MWP2 and MWP3 indicates these materials effectively preserve the seeds' visual quality, with aluminium foil in multiwall paper bag particularly preventing colour degradation due to its superior barrier properties.

Table 3: Colour Changes in Cumin Seed 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
MWP1	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	WD	WD	WD	WD	WD	WD	WD	WD
MWP2	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
MWP3	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
MWP4	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	WD	WD	WD	WD	WD	WD	WD

P.M- Packaging Materials
[**MWP1:** Multiwall Paper Bag without coating/ lamination – Control; **MWP2:** Multiwall Paper Bag laminated with MET PET; **MWP3:** Multiwall Paper Bag laminated with Aluminium foil; **MWP4:** Multiwall Paper Bag with wax coating] NC- No change
WD- Whitish discoloration

Aroma Changes in Cumin Seeds

The aroma changes in cumin seeds are summarized in Table 4. In MWP1 (Multiwall Paper Bag without coating/lamination), no aroma change (NC) was observed up to 132 days, after which a mushy odour (MO) developed and became more pronounced throughout the storage period. In MWP2 (Multiwall Paper Bag laminated with MET PET) and MWP3 (Multiwall Paper Bag laminated with Aluminium foil), no aroma change (NC) was observed during the entire storage period. In MWP4 (Multiwall Paper Bag with wax coating), no aroma change was noted until day 139, after which a mushy odour developed and intensified by the end of storage. The development of off-odours suggests microbial growth, likely due to moisture absorption. Paper bags without coating/lamination are more susceptible to moisture, leading to higher microbial contamination risk. The aluminium foil and MET PET provide barriers to moisture, light, and oxygen, which helped preserve the aroma and quality of the cumin seeds.

Table 4: Aroma Changes in Cumin Seed 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**
MWP1	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	BO	BO	BO	BO	BO	BO	BO	BO
MWP2	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
MWP3	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
MWP4	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	MO	MO	MO	MO	BO	BO	BO

P.M- Packaging Materials
[**MWP1:** Multiwall Paper Bag without coating/ lamination – Control; **MWP2:** Multiwall Paper Bag laminated with MET PET; **MWP3:** Multiwall Paper Bag laminated with Aluminium foil; **MWP4**: Multiwall Paper Bag with wax coating], **NC**- No change, **MO**- Mushy odour, **BO**- Bad odour

Microbial Growth in Cumin Seeds

The microbial growth results are summarized in Table 5. In MWP1 (Multiwall Paper Bag without coating/lamination), no microbial growth (NG) was observed on cumin seeds up to day 132, after which fungal growth (FG) was detected and continued throughout the storage period (Figure 5). In MWP2 (Multiwall Paper Bag laminated with MET PET) and MWP3 (Multiwall Paper Bag laminated with Aluminium foil), no microbial growth was observed during the entire storage period. In MWP4 (Multiwall Paper Bag with wax coating), no microbial growth was observed until day 139, but fungal growth (FG) was detected starting from day 146 and persisted through the rest of the storage. Microbial growth, particularly fungal contamination, is driven by moisture and oxygen availability, and the packaging material plays a critical role in limiting it. The lack of a moisture barrier in MWP1 allowed moisture buildup, promoting fungal growth. MET PET and aluminium foil offer effective barriers to moisture and oxygen, preventing fungal contamination. Although lamination enhances moisture resistance, it was insufficient in MWP4 to fully prevent moisture ingress, leading to fungal growth. The presence of fungi or moulds in spices is often attributed to insufficient drying, inadequate barrier properties of packaging materials, and improper storage conditions in warehouses. Elevated humidity levels can foster fungal growth, leading to spoilage and potential public health risks. In many cases, microbial populations found in spices are likely commensal organisms that survive the drying and storage processes. Soil and air serve as primary sources of contamination for crude spices in the field, with fungi being identified as the most predominant contaminants [23,24]. However, cumin seeds received were thoroughly dried with adequate initial moisture content, which was further studied at constant storage conditions so that the impact of packaging materials on the shelf life could be evaluated.

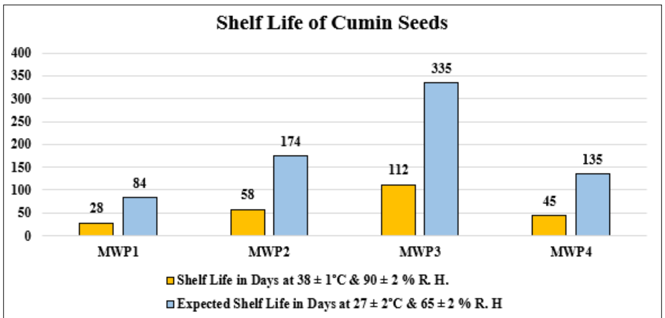
Table 5: Microbial Growth in Cumin Seed During Storage in Different Packaging Materials

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
MWP1	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	FG	FG	FG	FG	FG	FG	FG	FG
MWP2	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG
MWP3	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG
MWP4	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	FG	FG	FG	FG	FG	FG	FG

P.M- Packaging Materials
[**MWP1:** Multiwall Paper Bag without coating/ lamination – Control; **MWP2**: Multiwall Paper Bag laminated with MET PET; **MWP3:** Multiwall Paper Bag laminated with Aluminium foil; **MWP4:** Multiwall Paper Bag with wax coating]
NG- No growth
FG- Fungus growth

Shelf Life of Cumin Seeds

The shelf life of cumin seeds stored in different packaging materials is shown in Figure 6. MWP1 (Multiwall Paper Bag without coating/lamination) had a shelf life of 84 days. MWP2 (Multiwall Paper Bag laminated with MET PET) lasted 174 days, significantly longer than the control. MWP3 (Multiwall Paper Bag laminated with Aluminium foil) offered the longest shelf life of 335 days, while MWP4 (multiwall paper bag with wax coating) lasted 135 days. The shorter shelf life in MWP1 is due to its limited ability to protect cumin seeds from moisture and oxygen, leading to microbial growth and spoilage. MET PET and aluminium foil provide strong barriers against moisture, oxygen, and light, extending shelf life and preserving seed quality. Aluminium foil, in particular, effectively prevents moisture and oxygen from affecting the cumin seeds. The wax coating in MWP4 offers some moisture resistance but is less effective than MWP2 and MWP3. Despite these improvements, multiwall paper bags laminated with MET PET and aluminium foil performed below expectations, likely due to the inability to create an airtight seal. The presence of valves and folds allows gases to pass through, reducing the barrier effectiveness. Improving the airtightness of these bags could significantly extend shelf life.



[**MWP1:** Multiwall Paper Bag without coating/ lamination Control; **MWP2:** Multiwall Paper Bag laminated with MET PET; **MWP3:** Multiwall Paper Bag laminated with Aluminium foil; **MWP4:** Multiwall Paper Bag with wax coating]

Figure 5: Shelf life of Cumin Seeds

Microbial growth was observed on Multiwall paper bag without coating/ lamination

Figure 6: Microbial Growth During Storage

Evaluation of Bulk Pack of Cumin seed for Transport Worthiness Trials

To assess the transport worthiness of four selected packaging materials, drop tests and vibration tests were conducted. None of the packages showed any rupture or seepage of the cumin seeds, indicating their effectiveness in protecting the contents. Packaging is essential for safeguarding products against various transportation challenges, and transport worthiness testing is crucial for predicting the stability and integrity of packaging during transit. The results of the vibration and drop tests performed on the nine packaging options are summarized in Table 6. These tests simulate real-world conditions, ensuring that packaging can withstand physical-mechanical hazards such as shocks, drops, and compression forces commonly encountered in distribution cycles. Effective packaging is not only about aesthetics; it must also protect products from potential transportation hazards. The successful performance of these nine sustainable packaging materials in rigorous testing underscores their reliability and effectiveness in maintaining product integrity throughout the shipping process.

Table 6: Evaluation of Bulk Pack of Cumin seeds for Transport Worthiness Trials

Packaging Materials	Vibration test		Drop test	
	External	Internal	External	Internal
MWP1	No damage	No damage	No damage	No damage
MWP2	No damage	No damage	No damage	No damage
MWP3	No damage	No damage	No damage	No damage
MWP4	No damage	No damage	No damage	No damage

[**MWP1:** Multiwall Paper Bag without coating/ lamination – Control; **MWP2:** Multiwall Paper Bag laminated with MET PET; **MWP3:** Multiwall Paper Bag laminated with Aluminium foil; **MWP4:** Multiwall Paper Bag with wax coating]

Conclusion

A comprehensive evaluation of various packaging materials, including transport worthiness tests and shelf life assessments, was conducted across four sustainable packaging options. The results showed that the multiwall paper bag, designed with specific specifications, meets both mechanical and transport criteria. Enhancements like metallization and aluminium foil layers addressed its limitations, extending the shelf life of cumin seeds to 335 days while maintaining a biodegradable and sustainable packaging solution. This balance of functionality and environmental responsibility makes the multiwall paper bag an ideal choice for sustainable food packaging in the export market, ensuring product integrity and supporting environmental sustainability.

Acknowledgement

The authors acknowledge the Spices Board India for the financial assistance.

Conflict of Interest

No conflict of interest.

References

1. Liem DG, In't Groen A, Van Kleef E (2022) Dutch consumers' perception of sustainable packaging for milk products, a qualitative and quantitative study. Food Qual Prefer 102: 104658.
2. Langley S, Phan Le NT, Brennan L, Parker L, Jackson M, et al. (2021) The good, the bad, and the ugly: food packaging and consumers. Sustainability 13: 12409.
3. Otto S, Strenger M, Maier Noth Schmid AM (2021) Food packaging and sustainability - consumer perception vs correlated scientific facts: a review. Journal of Cleaner Production 298: 126733.
4. Patra D, Henley SC, Benefo EO, Pradhan AK, Shirmohammadi A (2022) Understanding and addressing food waste from confusion in date labelling using a stakeholders' survey. J Agric Food Res 8:100295.
5. (2024) Smithers Pira, The Future of Global Packaging to 2028 https://www.smithers.com/services/market-reports/packaging/the-future-of-global-packaging-to-2028.
6. Iva Jestratijevic, Irina Maystorovich, Urška Vrabič Brodnjak (2022) The 7 Rs sustainable packaging framework: Systematic review of sustainable packaging solutions in the apparel and footwear industry, Sustainable Production and Consumption 30: 331-340.
7. White A, Lockyer S (2020) Removing plastic packaging from fresh produce – what's the impact? Nutr Bull 45: 35-50.
8. Gondaliya SB, Khatrani TJ, Soni KK, Yogesh K Baravalia (2018) Consequence on long term storage on phytochemical attributes of cumin (Cuminum cyminum, L.) from districts of north Gujarat, India. Industrial Crops and Products 111: 908-913.
9. Gupta D (2013) Comparative analysis of spices for their phenolic content, flavonoids content and antioxidant capacity. Am Int J Res Formal Appl Nat Sci 4: 38-42.
10. Iness BR, Soumaya B, Wissem AW, Ibtissem H, Ferid L, et al. (2010) Essential oils, phenolics, and antioxidant activities of different parts of cumin (Cuminum cyminum, L.). J Agri Food Chem 58: 10410-10418.
11. Raju M, Nagarajan R (2024) Export Performance of Spices in India: An Empirical Analysis. Bodhi International Journal of Research in Humanities Arts and Science 8: 180-187.
12. Sandhya K (2023) Production volume of cumin in India FY 2015-2023. Statista. https://www.statista.com/statistics/1039665/india-cumin-production-volume/.
13. Pochont Nitin Ralph, Mohammad Noor Mohammad, Bodepu Thrinadh Pradeep, Vijaya Kumar P (2020) A comparative study of drying kinetics and quality of Indian red cumin seed in solar hybrid greenhouse drying and open sun drying, Materials Today: Proceedings 21: 286-290.
14. Baele M, Vermeulen A, Adons D, Peeters R, Vandemoortele A, et al. (2021) Selecting packaging material for dry food products by trade-off of sustainability and performance: A case study on cookies and milk powder, Packaging Technology and Science 34: 303-318.
15. AOAC (2003) Official Methods of Analysis of the AOAC International. Washington, DC: Association of Official Analytical Chemists. Washington, USA.
16. (1987) IS 7028-4. Performance tests for complete, filled transport packages, Part 4: Vertical impact drop test [TED 24: Transport Packages] 2-8.
17. (2002) IS 7028-2. Performance Tests for Complete, Filled Transport Packages, Part 2: Vibration Test at Fixed Low Frequency [TED 24: Transport Packages] 1-3.
18. El Sayed, Ayat, El Wahab M, El Shal HM, Abd Allah, et al. (2021) Effect of Moisture Content on Physical and Engineering Properties of Some Seeds. Zagazig Journal of Agricultural Research 48: 387-399.
19. Bell LN, Labuza TP (2000) Moisture Sorption: Practical Aspects of Isotherm Measurement and Use. American Association of Cereal Chemists 2. https://www.researchgate.net/publication/31720841_Moisture_Sorption_Practical_Aspects_of_Isotherm_Measurement_and_Use_LN_Bell_TP_Labuza.
20. Natalia Putri Erva Simbolon, Anang Mohammad Legowo, Bhakti Etza Setiani (2019) Estimation of Age Save Pasta Spice for Dekke Mas Na Niura with the Accelerated Shelf Life Test (ASLT) Method Arrhenius Equation. Journal of Applied Food Technology 6: 1-6.
21. Obse Fikiru, Hana Zinabu Dulo, Sirawdink Fikreyesus Forsido, Yetenayet B Tola, Tessema Astatkie (2024) Effect of packaging materials and storage duration on the functional

quality of red-hot peppers (Capsicum annum L.) pods, Heliyon 10: e32921.

22. Adrienne L Voelker, Abigail A Sommer, Lisa J Mauer (2020) Moisture sorption behaviors, water activity-temperature relationships, and physical stability traits of spices, herbs, and seasoning blends containing crystalline and amorphous ingredients. Food Research International 136: 109608.
23. Rani SK, Saxena N (2022) Fungal Contamination of some Common Spices. J Plant Sci Curr Res 5: 014.
24. Omorodion Nnenna JP (2020) Effect of different storage conditions on the microbial profile of some commonly used spices in Nigeria. Journal of Multidimensional Research & Review 1: 91-104.