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Management of *Rhyzopertha dominica* (Fab.) by Hermetic Bags and Impact on Quality Attributes of Stored Wheat

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Abstract: Wheat is one of the most important cereal crop, undergoes huge economic losses during storage by insect-pest infestations especially *Rhyzopertha dominica*. Management with chemical insecticides led to development of resistance among insect-pests of stored grains including *R. dominica*, which threatens its status as a reliable fumigant. So, it arises the need to explore some alternative insect-pest control. Keeping in view for exploring the alternatives, hermetic storage bags (HSBs) viz. HSB-1, HSB-2, HSB-3 were compared against traditional storage bags viz. Polypropylene woven and Jute bag to manage *R. dominica* under natural and artificial infestation conditions in stored wheat for a period of 180 days. The results revealed that no F_1 progeny emergence of *R. dominica* was observed under natural condition, while little emergence till 90 days of storage under artificial condition in all the hermetic bags. On comparing with traditional PP woven and jute bags, emergence and multiplication of *R. dominica* was observed throughout the storage period. Further, all the hermetic storage bags showed very less grain damage, weight loss along with maintaining grain moisture content and germination rate of wheat when compared to traditional bags under both the conditions throughout the storage period. Among gas exchanges, hermetic bags had maximum $CO_2$with more depleted level of O_2, while atmospheric level of CO_2 and $O_2$was observed in traditional bags. Comparison of all the hermetic bags showed HSB-3 is the best option to manage *R. dominica* along with maintaining other quality parameters with least gas exchange for long term storage of wheat. Thus, hermetic bags offer agricultural businesses a dependable, affordable, and environmentally responsible alternative that helps them protect their harvests and increase their profitability.

Keywords: Wheat**,** Hermetic bags, Storage, *Rhyzopertha dominica,* Gaseous content

Wheat crop is widely cultivated as a cool season annual crop which contributes about 35% of total food grain production of the country. In India, it was sown on an area of 305.0 lakh hectares with a production and productivity of 106.8 million tonnes and 35.07 quintals per hectare, respectively, during 2021-22 (Anonymous 2021). Wheat productivity per unit area has increased because of various practices which has further intensified concern for its proper storage. As the storage of wheat has been affected by various biotic and abiotic factors. Among various biotic factors, insect-pests played vital role for the post- harvest losses and among different stored grains, wheat found to be 2.5% more susceptible to be damaged by insects (Vishwakarma et al 2019). These losses can be reduced by integration of scientific storage procedures with ecofriendly natural materials.

Rhyzopertha dominica (Fab.) (Coleoptera: Bostrichidae) is the major threatening insects with cosmopolitan distribution pattern. It is primary insect-pest, which is highly destructive cause quantitative damage to stored wheat, corn and rice. Both the larval and adult stages of *R. dominica* cause damage, which lead to severe weight loss, bad odor due to insect secretions, reduction in nutrient contents and germination ability of the stored wheat. Use of chemicals *i.e.* synthetic insecticides and fumigants have been a popular strategy in developing countries for preventing insect-pests in grain during storage. The extensive use of phosphine has led to development of resistance among insect-pests of stored grains including *R. dominica* (Collins et al 2017), which threatens its status as a reliable fumigant.

Thus, an alternative is required to manage *R. dominica* in stored wheat to avoid post-harvest losses. Hermetic bags are the game changer in grain storage. Grain storage in these airtight, moisture-resistant bags create a controlled environment that protects grains from external environment (Lane and Woloshuk 2017). Nevertheless, there aren't many thorough research conducted in India on how the hermetic bags stored wheat affect insect-pests. Therefore, a study was conducted to compare the effectiveness of hermetic bags used globally such as Vestegaard, Ecotact, Save Grain against traditional storage bags *i.e.* Polypropylene (PP) woven and jute bag (JB) for storage of wheat by managing *R. dominica* as well as maintaining quality parameters of wheat under two conditions *i.e.* natural and artificial. Our research sheds light on how these kinds of bags for packing can assist farmers make better choice for preserving wheat and lowering post-harvest losses by maintaining its quality.

MATERIAL AND METHODS

Storage bags and description : The present investigations were conducted in the laboratory of Department of Processing and Food Engineering, Punjab Agricultural University (PAU), Ludhiana to study the effectiveness of hermetic storage bags (HSB) *i.e.* Vestergaard (HSB-1), Save Grain (HSB-2) and Ecotact (HSB-3) against two traditional storage bags like Polypropylene woven (PPW) and Jute bag (JB). The brand, composition, thickness and bag supplier are included in Table 1. All bags were available in 50 kg capacity except PPW and JB having 10 kg capacity. However, for the study purpose the smaller units (10 kg capacity) were modified without altering the properties (Paudyal et al 2017).

Grain sample preparation: The wheat grain var. PBW 824 (locally popular in Punjab, India), procured from Director (Seeds) Punjab Agricultural University, Ludhiana. Wheat grains (300 kg) were kept in metallic drum (1 tonne capacity) and treated with the aluminum phosphide @ 1 tablet of 3g in the laboratory of Department of Processing and Food Engineering, Punjab Agricultural University, Ludhiana. The drum was kept closed till 7 days for proper fumigation to remove any hidden insect-pest infestation for further experimentation. The wheat grains of 200 kg were kept in metallic drum without giving any disinfestation treatment.

Rearing of the test insect: Test insect (*Rhyzopertha dominica*) were collected from naturally infested farmer's field. The culture was reared on disinfested wheat grains filled up to 1/3rd capacity of plastic jars (500 ml), covered with muslin cloth and tightened with rubber band, to ensure ventilation avoiding the escape of insects. These jars were kept in BOD incubator (27±2^{O}C and relative humidity 75±5%) for further multiplication. After one month, *R. dominica* adults were shifted from old jars to new jars to avoid any kind of fungal infection. Pure culture was used to conduct the experiments.

Experimental set up and sampling: The experimental plan was designed by factorial CRD with five treatments (in quadruple) *viz.* HSB-1, HSB-2, HSB-3, PPW and JB with two conditions *i.e.* un-infested (natural condition) and infested (artificial condition). Each bag of 10 kg capacity was filled with wheat to its optimum storage capacity, including the closure space. Wheat grains were filled in various bags without giving any disinfestation treatment under natural condition. While, the freshly emerged mixed adult population of *R. dominica* @ 10 insects / kg grains were released in each bag under artificial condition. After filling the bags with wheat grains, the bags were sealed air-tight using nylon tags. The rubber septa were fixed on all bags for measuring the CO_2 and O_2 concentrations. All these bags were further packed in jute bag liners to get them protected from any kind of damage. The samples were then stacked on pallets maintaining the stack height of 4.00 feet and away from 1 metre from wall having storage room mean temperature varied from 25.1-32.9°C and relative humidity varied from 39-74% throughout the storage studies (May to October 2022). The sample size of 500g were drawn every month for recording quality parameters *i.e.* F_1 adult emergence (number) insect count was made from 100 g sample (Syed et al 2022) , grain damage (%), weight loss (%) (Boxall, 2002), grain moisture (%)(AOAC, 2016), germination (%) (ISTA, 2015) and CO_2 & O_2 (%) by using headspace gas analyser (GS3/P, U.K.) to measure concentrations till 180 days. The bags were discarded after taking the observations.

RESULTS AND DISCUSSION

Effect of various storage bags on adult emergence: The importance of HSBs in relation to the adult emergence of *R. dominica* was evident when comparing natural and artificial infestation conditions. No F_1 progeny emergence was observed naturally, there was a subtle emergence (≤1.66 adults) within the initial 90 days of storage under artificial conditions. Adult emergence rates remained consistent in all HSBs throughout the storage period, regardless of whether the conditions were natural or artificial except till 90 days under artificial condition. However, the emergence patterns observed in PPW and JB were noteworthy. JB displayed the highest emergence numbers (16.75 adults) under artificial condition, while 14.00 adults under natural condition by the

Table 1. Detail of different bags used in study

Type of bags	Description of bags	Thickness (µm)	Capacity (Kg)	Make
HSB-1	Pesticide free, woven PP structurally reinforced with a laminated layer and hermetic film with a high quality gas barrier layer	30	50	Vestergaard
HSB-2	Pesticide free, single multilayer polymeric bags with food grade recyclable plastic resins	82	50	Ecotact
HSB-3	Pesticide free, single multilayer polymeric bags with advanced technology and gas barrier polymer inside	80	50	Savegrains
PPW	-	-	10	Local market, Ludhiana
JB (Untreated control)	-	-	10	Local market, Ludhiana

180th day of storage. In contrast, PPW bag showed slightly lower infestation levels compared to JB, with emergences of 9.75 and 12.00 adults in number under natural and artificial conditions, respectively (Table 2). Hermetic storage bags effectively hindered damage by pulse beetles under both artificial and natural infestation conditions through mechanisms such as insect reproduction prevention and lack of aeration (Yewle et al 2020, Mutungi et al 2014). A hermetic environment, as emphasized by Kiobia et al (2020), disrupts insect development, metamorphosis, and reproduction due to oxygen deprivation.

Effect of various storage bags on quality parameters: The degree of insect infestation closely correlates with grain damage and losses during storage, as highlighted in studies by Yewle et al (2021) and Akrofi et al (2023). Minimal grain damage percentages (≤ 0.87) were observed across all hermetic storage bags (HSBs), significantly differing from PPW and JB under both natural and artificial conditions across various storage intervals. Among all HSBs, HSB-3 exhibited the lowest grain damage, with values of ≤0.65 under natural condition and ≤1.61 under artificial condition. Conversely, JB showed the highest grain damage, reaching 31.42 and 51.85% under natural and artificial conditions, respectively (Table 3). Hermetic storage bags demonstrated superior efficacy in minimizing grain weight loss when storing wheat, with HSB-3 exhibiting the least loss (≤0.15), followed by HSB-2 (≤0.19) and HSB-1 (≤0.25) under natural condition. This trend persisted under artificial condition, albeit with slightly higher losses. HSB-3 proved to be the most efficient, with ≤0.50% grain weight loss. In contrast, JB-stored wheat experienced maximum grain weight loss (≤25.63 and 39.23), followed by PPW (≤14.74 and 26.19) under natural and artificial conditions, respectively, over a 180-days of storage period. PPW and JB, being non-airtight, facilitate gaseous exchange, aligning with findings from Akrofi et al (2023).

The study highlighted the substantial decrease in grain damage when wheat was stored in hermetic bags under natural condition, contrasting with significant damage seen in PPW and JB over a six-month storage period. Anankware (2013) investigated the impact of various storage bags on *S. zeamais* and *P. truncatus* in maize grains, finding that prolonged storage in conventional bags significantly increased insect-induced damage. This supports earlier research by Atta et al (2020), Darfour and Rosentrater (2020), Yewle et al (2021), and Saini et al (2022), emphasizing the effectiveness of hermetic bags in controlling pulse beetle or bruchid damage compared to conventional bags. Wasala et al (2016) observed increased grain weight loss due to insect pests during the 30 to 150 days storage period. Study similarly showed significant weight loss in both infested and un-infested non-hermetic bags, while no significant difference was found among hermetic bags.

The moisture content of wheat stored in all HSBs was consistent and minimal with HSB-3 exhibiting the lowest moisture content (≤11.37 and 11.38 %) under natural and artificial conditions, respectively. Conversely, grain moisture was highest in JB-stored wheat (≤16.00 and 16.11%), followed by PPW bags (≤14.45 and 14.48%) under natural and artificial conditions, respectively. The HSBs maintained favourable moisture levels when compared with initial moisture (11.34%), making them suitable for wheat storage. The hermetic bags outperformed ordinary bags in retaining moisture content consistently across different storage conditions, consistent with previous findings (Tubbs et al 2016, Bhandari et al 2018, Yewle et al 2021) was associated

Table 2. Effect of different bags on adult emergence in stored wheat

Storage conditions		Different bags	Storage (Days)					
			30	60	90	120	150	180
Adult emergence (number)	Natural (Un-infested)	HSG-1	0.00^{l}	0.00^{l}	0.00^{l}	0.00^{l}	0.00^{l}	0.00^{l}
		HSG-2	0.00^{l}	0.00^{l}	0.00^{l}	0.00^{l}	0.00^{l}	0.00^{l}
		HSG-3	0.00^{l}	0.00^{l}	0.00^{l}	0.00^{l}	0.00^{l}	0.00^{l}
		PPW	1.50^{de}	3.25^{gh}	3.75^{gh}	3.50^{gh}	5.50^{g}	9.75^{cd}
		JB	1.50^{de}	5.25^{g}	3.75^{cd}	5.50^{g}	9.50^{cd}	14.00^{b}
	Artificial (Infested)	HSG-1	1.66^{i}	1.33^{ij}	1.33^{ij}	0.00^{l}	0.00^{l}	0.00^{l}
		HSG-2	1.33^{ij}	1.33^{ij}	1.00^{j}	0.00^{l}	0.00^{l}	0.00^{l}
		HSG-3	1.00^{j}	1.00^{j}	0.66^{k}	0.00^{l}	0.00^{l}	0.00^{l}
		PPW	2.50^{h}	4.25^{gh}	7.75^{de}	9.50^{cd}	10.50^{de}	12.00^{b}
		JB	5.25^{g}	7.25^{ef}	11.25^{bc}	13.25^{b}	14.75^{b}	16.75^{a}

Mean values followed with different superscripts for different parameters significantly differ ($p<0.05$) using Tukey's test
At zero day of storage: No adult emergence, no grain damage, no weight loss

Table 3. Effect of different bags on quality parameters of stored wheat

Storage conditions		Different bags	Storage (Days)					
			30	60	90	120	150	180
Grain damage (%)	Natural (Un-infested)	HSG-1	0.82^{n}	0.85^{n}	0.87^{n}	0.85^{n}	0.87^{n}	0.83^{n}
		HSG-2	0.67^{o}	0.67^{o}	0.62^{o}	0.62^{o}	0.65^{o}	0.62^{o}
		HSG-3	0.63^{o}	0.60^{o}	0.65^{o}	0.60^{o}	0.62^{o}	0.65^{o}
		PPW	1.42^{m}	3.60^{k}	7.33^{i}	10.32^{h}	15.07^{g}	20.75^{e}
		JB	1.80^{m}	4.27^{j}	9.50^{h}	13.62^{g}	22.87^{e}	31.42^{c}
	Artificial (Infested)	HSG-1	2.45^{l}	2.68^{l}	2.69^{l}	2.66^{l}	2.65^{l}	2.64^{l}
		HSG-2	1.73^{m}	1.70^{m}	1.65^{m}	1.63^{m}	1.62^{m}	1.62^{m}
		HSG-3	1.61^{m}	1.60^{m}	1.55^{m}	1.56^{m}	1.53^{m}	1.52^{m}
		PPW	2.82^{l}	4.85^{j}	10.40^{h}	19.22^{f}	26.65^{d}	37.27^{c}
		JB	3.22^{k}	6.32^{i}	13.17^{g}	22.10^{e}	39.20^{b}	51.85^{a}
Weight loss (%)	Natural (Un-infested)	HSG-1	0.21^{mn}	0.23^{mn}	0.25^{mn}	0.22^{mn}	0.25^{mn}	0.23^{mn}
		HSG-2	0.19^{n}	0.19^{n}	0.15^{n}	0.14^{n}	0.15^{n}	0.13^{n}
		HSG-3	0.15^{n}	0.13^{n}	0.14^{n}	0.12^{n}	0.13^{n}	0.14^{n}
		PPW	0.37^{m}	1.32^{k}	3.27^{i}	5.43^{h}	9.12^{g}	14.74^{e}
		JB	0.47^{m}	1.69^{jk}	4.75^{f}	8.96^{d}	16.85^{b}	25.63^{a}
	Artificial (Infested)	HSG-1	0.71^{l}	0.82^{l}	0.83^{l}	0.80^{l}	0.80^{l}	0.78^{l}
		HSG-2	0.56^{m}	0.54^{m}	0.53^{m}	0.50^{m}	0.50^{m}	0.50^{m}
		HSG-3	0.50^{m}	0.50^{m}	0.45^{m}	0.46^{m}	0.40^{m}	0.40^{m}
		PPW	1.01^{k}	2.22^{j}	6.53^{h}	12.47^{f}	18.01^{d}	26.19^{c}
		JB	1.39^{k}	3.48^{i}	8.90^{g}	16.12^{e}	27.54^{b}	39.23^{a}
Grain moisture (%)	Natural (Un-infested)	HSG-1	11.38^{nop}	11.47^{lmno}	11.42^{lmno}	11.47^{lmno}	11.48^{lmno}	11.48^{lmno}
		HSG-2	11.35^{nop}	11.37^{nop}	11.34^{nop}	11.38^{mop}	11.43^{lmno}	11.41^{lmno}
		HSG-3	11.32^{op}	11.36^{nop}	11.34^{nop}	11.35^{nop}	11.33^{nop}	11.37^{nop}
		PPW	11.52^{klmn}	11.95^{j}	12.67^{h}	13.17^{g}	13.90^{e}	14.45^{d}
		JB	12.40^{i}	13.70^{f}	14.52^{d}	14.87^{c}	15.47^{b}	16.00^{a}
	Artificial (Infested)	HSG-1	11.40^{lmno}	11.47^{lmno}	11.45^{lmno}	11.50^{lmno}	11.49^{lmno}	11.52^{klmn}
		HSG-2	11.39^{nop}	11.38^{nop}	11.40^{lmno}	11.38^{mop}	11.4^{lmno}	11.42^{lmno}
		HSG-3	11.36^{nop}	11.37^{nop}	11.38^{nop}	11.35^{nop}	11.37^{nop}	11.38^{nop}
		PPW	11.51^{klmn}	12.00^{i}	12.77^{h}	13.19^{g}	13.95^{e}	14.48^{d}
		JB	12.42^{i}	13.81^{f}	14.61^{d}	14.92^{c}	15.51^{b}	16.11^{a}
Seed germination (%)	Natural (Un-infested)	HSG-1	89.75^{a}	89.50^{a}	89.25^{a}	89.50^{a}	89.25^{a}	89.25
		HSG-2	90.00^{a}	89.50^{a}	89.50^{a}	89.25^{a}	90.00^{a}	89.25^{a}
		HSG-3	90.25^{a}	90.25^{a}	89.75^{a}	90.00^{a}	89.50^{a}	90.50^{a}
		PPW	89.75^{a}	85.50^{b}	80.00^{d}	76.25^{e}	73.25^{f}	69.75^{g}
		JB	88.50^{a}	83.50^{c}	78.25^{d}	71.25^{g}	67.25^{h}	62.00^{i}
	Artificial (Infested)	HSG-1	89.00^{a}	89.00^{a}	88.50^{a}	88.75^{a}	89.25^{a}	89.00^{a}
		HSG-2	89.25^{a}	89.75^{a}	89.00^{a}	89.00^{a}	89.00^{a}	89.25^{a}
		HSG-3	89.75^{a}	89.50^{a}	89.32^{a}	89.52^{a}	89.50^{a}	89.37^{a}
		PPW	88.27^{a}	83.00^{c}	76.50^{e}	68.50^{g}	61.00^{i}	51.00^{k}
		JB	87.25^{a}	80.00^{d}	73.50^{f}	66.50^{h}	53.75^{k}	46.25^{l}

Mean values followed with different superscripts for different parameters significantly differ ($p<0.05$) using Tukey's test
At zero day of storage: seed germination-90.25%, grain moisture-11.34%

with reduced metabolic activity of insects (Mutambuki et al 2019). The conventional bags exhibited significant fluctuations in moisture content, particularly observed in PPW and JB, where moisture levels ranged from 11.52 to 14.45% and 11.51 to 14.48% under natural and artificial conditions, respectively, over a 30-180 day storage period. This variability in moisture content in conventional bags was also reported by Afzal et al (2020) which may be attributed to fungal growth on insect-injured grains.

HSB-3 emerged as the most effective in promoting maximum germination in stored wheat, with rates reaching ≤90.50% and 89.75% under natural and artificial conditions, respectively, statistically comparable to other HSBs and storage periods. Interestingly, the germination rate at day zero stood at a robust 90.25%, statistically similar to all three hermetic bags. Conversely, germination rates were lower in jute and PPW bags, with the most significant reduction observed in jute bags (62.00 and 46.25%) under natural and artificial conditions, respectively after 180 days of storage, followed by PPW bags. Samples stored in hermetic bags consistently exhibited higher germination rates compared to PPW and jute bags, consistent with findings by Yewle et al (2021). The germination was impaired in PPW and JBs under both conditions, with more pronounced reductions in germination observed under artificial conditions compared to natural conditions. The study unequivocally demonstrated that germination rates varied significantly depending on storage conditions and bag types used, aligning with findings by Abbas et al (2018), who reported no germination losses when grains were stored in hermetic bags. Similarly, Awal et al (2017) found that rice stored in PICS and GrainPro bags outperformed other conventional storage structures in terms of weight and germination losses. The use of hermetic bags to preserve seed quality and ensure successful storage has been consistently supported by previous studies, including by Abbas et al (2018), Likhayo et al (2018) and Afzal et al (2020).

Table 4. Effect of different bags on carbon dioxide and oxygen concentration in stored wheat

Storage conditions	Different bags	Storage (Days)					
		30	60	90	120	150	180
Natural (Un-infested)	CO_2 (%)						
	HSG-1	3.70^{l}	5.17^{jk}	6.27^{ghi}	7.00^{fg}	7.72^{ef}	9.34^{bc}
	HSG-2	4.57^{kl}	5.37^{ijk}	6.49^{gh}	7.28^{efg}	8.00^{de}	9.55^{bc}
	HSG-3	5.73^{hij}	7.00^{fg}	8.96^{cd}	9.23^{bc}	9.96^{b}	12.18^{a}
	PPW	0.04^{m}	0.04^{m}	0.04^{m}	0.04^{m}	0.04^{m}	0.04^{m}
	JB	0.04^{m}	0.04^{m}	0.04^{m}	0.04^{m}	0.04^{m}	0.04^{m}
	O_2 (%)						
	HSG-1	20.62^{a}	19.90^{b}	18.97^{c}	15.31^{f}	12.65^{h}	11.04^{k}
	HSG-2	19.22^{c}	16.85^{e}	14.68^{g}	12.91^{h}	12.35^{i}	10.79^{k}
	HSG-3	20.85^{a}	18.08^{d}	15.47^{f}	12.83^{h}	11.77^{j}	10.11^{l}
	PPW	20.90^{a}	20.90^{a}	20.90^{a}	20.90^{a}	20.90^{a}	20.90^{a}
	JB	20.90^{a}	20.90^{a}	20.90^{a}	20.90^{a}	20.90^{a}	20.90^{a}
Artificial (Infested)	CO_2 (%)						
	HSG-1	5.78^{kl}	7.65^{j}	8.52^{ij}	10.26^{gh}	11.85^{ef}	13.72^{cd}
	HSG-2	4.68^{l}	7.72^{j}	9.55^{hi}	11.86^{ef}	13.66^{cd}	15.58^{b}
	HSG-3	4.96^{kl}	6.12^{k}	11.25^{fg}	12.69^{de}	14.65^{bc}	17.97^{a}
	PPW	0.04^{m}	0.04^{m}	0.04^{m}	0.04^{m}	0.04^{m}	0.04^{m}
	JB	0.04^{m}	0.04^{m}	0.04^{m}	0.04^{m}	0.04^{m}	0.04^{m}
	O_2 (%)						
	HSG-1	20.34^{a}	17.03^{b}	12.52^{d}	9.95^{f}	6.47^{ghi}	6.07^{hij}
	HSG-2	20.90^{a}	17.56^{b}	12.45^{d}	9.07^{fg}	6.08^{hij}	5.89^{ijk}
	HSG-3	20.60^{a}	15.15^{c}	11.05^{e}	6.58^{gh}	4.86^{jk}	4.13^{k}
	PPW	20.90^{a}	20.90^{a}	20.90^{a}	20.90^{a}	20.90^{a}	20.90^{a}
	JB	20.90^{a}	20.90^{a}	20.90^{a}	20.90^{a}	20.90^{a}	20.90^{a}

Mean values followed with different superscripts for different parameters significantly differ ($p<0.05$) using Tukey's test
At zero day of storage: concentration of CO_2: 0.04% and O_2: 21.00%

HSB-3 exhibited notable differences in CO_2 and O_2 levels compared to other HSBs. Maximum CO_2 level was recorded in HSB-3, reaching ≤ 12.18% and ≤ 17.97% under natural and artificial conditions, respectively. Conversely, there was a significant decrease in O_2 level in HSB-3, with reductions of ≥10.11% and ≥4.13% observed under natural and artificial conditions, respectively. HSB-2 showed even higher CO_2 level and greater decrease in O_2 level compared to HSB-1 (Table 4). Throughout the storage period and under both conditions, PPW and JB maintained atmospheric levels of CO_2 (0.04%) and O_2 (20.90%). Yewle et al (2022) observed 7% oxygen in un-infested and 6% in infested hermetic bags after 6 months. In current study, oxygen levels were 14.47% naturally and 10.39% artificially, aligning with their trend. The significant CO_2 increase due to aerobic metabolism. Hermetic storage effectively manages oxygen compared to conventional, which maintains atmospheric levels.

The mean data on various observation showed that under natural condition, there was no F_1 adult emergence (number) of *R. dominica* in any of the three HSBs, while minimal F_1 adult emergence (0.44 to 0.72 adults) occurred under artificial condition. It was observed that under artificial condition, mean adult emergence (number) was statistically at par in HSB-2 and HSB-3, while differed significantly in HSB-1. JB exhibited the highest mean adult emergence (number), followed by PPW bag under both conditions. For grain damage, HSB-3 had the lowest mean grain damage (0.62 and 1.56%), which was at par with HSB-2 (0.64 and 1.65%) and differed significantly from HSB-1 (0.84 and 2.63%) under both natural and artificial conditions, respectively. Conversely, JB had the highest mean grain damage, followed by PPW bags under both the conditions. Similar trend was observed for mean grain weight loss (Table 5). When both the conditions were compared, highest mean grain damage and mean weight loss were observed under artificial condition. Mean seed germination of stored wheat was highest in HSB-3 (89.83 and 89.49%) under natural and artificial conditions, respectively, and was statistically at par with HSB-2 and HSB-1. JB exhibited the lowest germination rate, followed by PPW bags stored wheat under both conditions. Grain moisture was lowest in HSB-3 (11.34 and 11.36%) under natural and artificial conditions, respectively and was statistically at par with HSB-2 and HSB-1. Conversely, JB had the highest moisture content, followed by PPW bags under both conditions. CO_2 level was highest in HSB-3, followed by HSB-2 and HSB-1 under both conditions, with a more significant rise under artificial condition. Oxygen level declined with increased CO_2, with the lowest O_2 content observed in HSB-3 under both conditions. The decline in O_2 occurred under artificial condition compared to natural

Table 5. Comparison of mean effect of different bags on insect parameters

Treatments	Parameters					
	Adult emergence (number)		Grain damage (%)		Weight loss (%)	
	Natural condition	Artificial condition	Natural condition	Artificial condition	Natural condition	Artificial condition
HSG-1	0.00[c]	0.72[c]	0.84[c]	2.63[c]	0.23[c]	0.79[c]
HSG-2	0.00[c]	0.55[d]	0.64[d]	1.65[d]	0.15[d]	0.52[d]
HSG-3	0.00[c]	0.44[d]	0.62[d]	1.56[d]	0.13[d]	0.45[d]
PPW	4.54[b]	7.25[b]	9.75[b]	16.86[b]	5.71[b]	11.07[b]
JB	6.58[a]	11.08[a]	13.91[a]	22.64[a]	9.72[a]	16.11[a]

Mean values in the column followed with different superscripts significantly differ (p<0.05) using Tukey's test

Table 6. Comparison of mean effect of different bags on quality parameters and gaseous concentrations

Treatments	Parameters							
	Germination (%)		Moisture (%)		CO_2 (%)		O_2 (%)	
	Natural condition	Artificial condition	Natural condition	Artificial condition	Natural condition	Artificial condition	Natural condition	Artificial condition
HSG-1	89.41[a]	88.91[a]	11.44[c]	11.47[c]	6.69[b]	9.63[c]	18.21[b]	12.06[b]
HSG-2	89.58[a]	89.20[a]	11.38[c]	11.40[c]	6.71[b]	10.51[b]	14.85[c]	11.61[c]
HSG-3	89.83[a]	89.49[a]	11.34[c]	11.36[c]	8.84[a]	11.27[a]	14.47[d]	10.39[d]
PPW	79.08[b]	71.37[b]	12.94[b]	12.98[b]	0.04[c]	0.04[d]	20.90[a]	20.90[a]
JB	75.12[c]	68.20[c]	14.49[a]	14.56[a]	0.04[c]	0.04[d]	20.90[a]	20.90[a]

Mean values in the column followed with different superscripts significantly differ (p<0.05) using Tukey's test condition. PPW and JB maintained atmospheric CO_2 and O_2 levels throughout the storage studies (Table 6).

CONCLUSION

The comprehensive analysis revealed that hermetic storage bags, particularly HSB-3 demonstrated superior performance across various parameters and effectively mitigated adult emergence, minimized grain damage, preserved seed germination and moisture content compared to conventional PPW and JBs under both natural and artificial storage conditions. Moreover, HSBs exhibited controlled CO_2 and O_2 levels, with HSB-3 showed the highest CO_2 concentration and lowest O_2 content, indicative of effective insect suppression. These findings underscored the efficacy of hermetic bag storage technology in preserving grain quality and preventing insect-pest infestation, highlighting its potential for enhancing food security and reducing post-harvest losses in agricultural storage systems.

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