International Journal of Agricultural Technology 2024 Vol. 20(1):213-230
Available online http://www.ijat-aatsea.com
ISSN 2630-0192 (Online)

Influence of vacuum packaging combined with storage condition on biochemical activities and quality of groundnut seed (*Arachis hypogaea* L.)

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Multha, N. and Sikhao, P. (2024). Influence of vacuum packaging combined with storage condition on biochemical activities and quality of groundnut seed (*Arachis hypogaea* L.). International Journal of Agricultural Technology 20(1):213-230.

Abstract The results showed that seeds stored in 760-gauge polypropylene bags at vacuum levels of -0.04 MPa and -0.06 MPa under controlled conditions exhibited the highest dehydrogenase enzyme activity, germination percentage and index, and also displayed the lowest free fatty acid content. Additionally, it was observed that the moisture content and water activity of seeds in all packaging materials remained consistent from the beginning to the end of the storage period.

Keywords: Free fatty acid, Dehydrogenase activity, Woven plastic bag, Polypropylene, Peanut

Introduction

Peanut is known as groundnuts (*Arachis hypogaea* L.), which belongs Fabaceae and hold significant economic importance as they can be cultivated year-round. Peanuts are widely grown across the globe, with approximately 41.4 million metric tons produced worldwide in the 2019/2020 season, showing a slight decrease from 42.79 million metric tons in 2018/2019 (International Nut and Dried Fruit Council, 2020). In the 2019/2020 production year, Thailand reported peanut cultivation on 93,258 rai of land, yielding a total of 31,097 tons, while the domestic demand for peanuts in Thailand stood at 126,178 tons. Due to increased processing demands, which outstrip production capacity, peanuts are imported from abroad. In 2019, Thailand imported 64,494 tons of peanuts, valued at 2053.66 million baht (Department of Agriculture, 2015; Office of Agricultural Economics, 2019). Peanuts are rich in oil, comprising 31-46 percent of their composition, followed by protein (20.7-25.3 percent), carbohydrates (21-37 percent), fiber (1.4-3.9 percent), and ash (1.2-2.3 percent) (Alhassan *et al.*, 2017). The high oil content in peanuts makes them susceptible to rapid quality deterioration through lipid oxidation, catalyzed mainly by factors such as

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oxygen, light, humidity, and high temperatures (Reed *et al*., 2002). Relative humidity and ambient temperature during storage are crucial factors influencing seed quality, directly tied to seed moisture content. Subtropical and tropical regions often experience unfavorable conditions for seed storage, with groundnut seeds harvested in the summer season losing approximately 50 percent of their viability within 4-5 months. Proper seed storage is essential to maintain germination and vigor, as high temperatures and relative humidity can rapidly degrade peanut seed quality. Environmental conditions during growth and harvest also play a significant role in seed quality and storability (Meena *et al*., 2017). One of the most common quality issues with peanut seeds is excessive aflatoxin contamination during postharvest processes like drying and shelling (Department of Agriculture, 2015). Controlling temperature, relative humidity, and using appropriate packaging materials can reduce aflatoxin contamination during storage (Duangpatra and Promchote, 2000). Maintaining low relative humidity levels, along with storing soybean kernels in aluminum foil bags, has been shown to delay seed deterioration, particularly in terms of phospholipid and protein contents of the mitochondrial inner membrane, germination, and germination velocity (Tatipata, 2009). A widely accepted approach to mitigating lipid autoxidation in peanut seeds is controlling the gas composition within the packaging, utilizing techniques such as vacuum packaging and careful temperature regulation (Sandhya, 2010). Kowalski *et al*. (1994) reported that vacuum pressure can inhibit the oxidation of linoleic acid, as oxygen is a primary catalyst for the oxidation of enclosed products. Therefore, packaging with minimal voids can effectively prevent oxidation (Anonymous, 2000). In general, seeds stored in sealed containers exhibit greater resistance to moisture fluctuations compared to seeds in permeable containers when subjected to ambient and cold storage conditions. The choice of packaging materials should consider factors such as seed type, quantity, packaging method, storage duration, storage temperature, and relative humidity of the storage area (Meena *et al.,* 2020). Vacuum technology minimizes quality loss by reducing insect activity, fungal growth, and metabolic processes within the seeds. In contrast, seeds stored under non-hermetic conditions tend to experience reduced quality, manifesting as increased fatty acid content and buoyancy index. Dry peanut seeds should be stored in containers that prevent moisture increase. According to Mutegi *et al*. (2013), peanuts stored in various types of bags showed different moisture levels after 6 months, with averages of 5.1% for polypropylene, 5.2% for polyethylene, and 5.3% for jute. Jute bags readily absorb moisture but provide good ventilation, whereas polypropylene and polyethylene bags do not absorb moisture but retain heat (Kennedy and Devereau, 1994). Combining polypropylene packaging with vacuum pressure can effectively maintain peanut seed quality, resulting in low acid and peroxide values, low relative electrical conductivity, and a higher germination rate compared to traditional plastic sacks. The reduced vacuum pressure within the packaging decreases oxygen levels and, consequently, oxidation (Anjian *et al*., 2016). The objective was to identify a seed storage method to be effectively preserved peanut seed quality under specific storage conditions and vacuum pressure levels, and to provide the guidelines for peanut seed and product storage to minimize quality loss during storage.

Materials and methods

Preparation of peanut seed for storage

A storage experiment was conducted over a period of 6 months, spanning from January 2023 to July 2023, at the Department of Plant Production Technology, School of Agricultural Technology, King Mongkut's Institute of Technology Ladkrabang. The research was done using 2-factor factorial experiment in a completely randomized design. Factor A was the packaging treatment, and Factor B was the storage condition. Peanut seeds were placed in two types packaging materials; woven plastic bags and polypropylene 760-gauge (PP), which were considered as control packaging materials. The vacuum levels employed for the polypropylene (PP) packaging were set at -0.02 MPa, -0.04 MPa, -0.06 MPa, and -0.08 MPa, respectively. Each bag contained a sample size of 410 g, and the packaging treatment was replicated three times. The polypropylene 760-gauge bags were sealed using a vacuum packaging machine (model BELTER-10), while the woven plastic bags were sealed through sewing. All packages were stored in two distinct environmental conditions; ambient conditions (approximately 35.5°C) and controlled conditions (13±2°C and 19±11% relative humidity) for 6 months. Sampling was conducted every 2 months to determine various quality parameters in all treatments, including free fatty acid content, dehydrogenase enzyme activity, seed moisture content, seed water activity, seed germination percentage in the laboratory, and seed germination index.

Free fatty acids content

The percentage of free fatty acids in the oil sample was determined by titrating the oil in neutralized ethanol (95%) using a NaOH solution, following the method outlined in AOCS (1998), specifically method no. Ca 5a-40. Three grams of the sample were placed into a clean, dry conical flask, along with 50 mL of 95% ethanol. The mixture was adequately stirred to ensure complete dissolution of the sample. Subsequently, 1–2 drops of phenolphthalein indicator were added, and the contents were titrated against a 0.1 N NaOH solution. The titration was carried out with continuous shaking until a pink color persisted for at least 30 seconds. The percentage of free fatty acids was then calculated as follows:

$$\% \text{ FFA as oleic acid} = \left(\frac{(A-B) \times N \times 28.2}{\text{Weight of oil sample (g)}} \right)$$

where

A = is the amount of sodium hydroxide solution used to titrate the sample (ml).

B = is the amount of sodium hydroxide solution used to titrate the Blank solution (ml).

N = is the concentration of the prepared sodium hydroxide solution.

28.2 = is the percentage by weight of oleic acid.

Dehydrogenase enzyme activity (OD Value)

Representative seeds (25) from each treatment were selected and preconditioned by soaking them in water overnight at room temperature. The seeds were chosen randomly, and their embryos were then excised. These embryos were immersed in a 0.25 percent solution of 2, 3, 5-triphenyl tetrazolium chloride and left in the dark for two hours at 40°C to allow for staining. Following staining, the seeds were thoroughly washed with water and subsequently soaked in 10 ml of 2-methoxy ethanol (methyl cellulose) and left overnight to extract the red-colored formazan. The intensity of the red color was measured using an ELICO UV-VIS spectrophotometer (model SC-159) equipped with a blue filter (470 nm), and methyl cellulose was used as the blank. The optical density (OD) value obtained was reported as dehydrogenase activity (Kittock and Law, 1968).

Seed moisture content

The moisture content of peanut seed was determined using the hot air oven method. The procedure involved the following steps: Weigh the aluminum can with its cover and record the initial weight as M1. Collect samples ranging from 5 to 10 grams of the seed and place them in an aluminum can. Weigh the can with the sample, recording this weight for each treatment with three replications as M2. Place the aluminum can, along with its cover, in a hot air oven set at 130°C for 1 hour (ISTA, 2019). After the prescribed period, remove the aluminum can from the hot air oven and place it in a desiccator for 30 minutes.

After cooling, weigh the aluminum can with the cover and the sample inside as M3. Calculate the seed moisture content using the following formula:

$$\text{Seed moisture content (\%)} = \left(\frac{M_2 - M_3}{M_2 - M_1} \right) \text{x } 100$$

where

M_1 = The weight in grams (to a minimum of three decimal places) of the aluminium can and its cover.

M_2 = The Weight in grams (to a minimum of three decimal places) of the aluminium can, its cover and its contents before drying.

M_3 = The weight in grams (to a minimum of three decimal places) of the aluminium can, its cover and its contents after drying.

Seed water activity

The determination of seed water activity was conducted using the RR Moisture instrument (RHINO, model HC2-AW-USB-SW), which measures water activity in seeds. The seeds were placed into probes and these probes were then positioned in the sample holder of the instrument. The instrument thenprovided readings of the seed water activity, which were recorded as the results of the study.

Germination percentage of seeds in laboratory condition

The percentages of peanut seed germination were determined using the between-paper method. Random samples of 50 seeds were selected, and these seeds were placed between two damp planting papers. The stack of papers with the seeds was then incubated in an environment where the temperature was controlled at 25°C. Germination was assessed by counting the number of normally germinated seedlings at both 5 days (as the first count) and 10 days (as the final count) following incubation (ISTA, 2019).

$$\text{seed germination (\%)} = \left(\frac{\text{number of normal seedlings}}{\text{number of cultivated seeds}} \right) \text{x } 100$$

Germination index

Peanut seeds were cultivated following the laboratory seed germination test method. The counting of normally germinated seeds was conducted on day 5 (as the first count) and day 10 (as the final count) (ISTA, 2019).

$$\text{germination index} = \sum \left(\frac{\text{number of normal seedlings in each day}}{\text{number of days after cultivation}} \right)$$

Data analysis

The experiment was designed as a 6 x 2 factorial experiment in a completely randomized design with three replications. Factor A represented the packaging treatments, while Factor B represented the storage conditions. The data were subjected to analysis of variance (ANOVA), and comparative analyses between means were conducted using the Duncan's New Multiple Range Test (DMRT) within the Statistical Analysis System (SAS).

Results

Free fatty acids content

The study investigated the effects of different packaging treatments on the preservation of peanut seeds over a 6-month period. The results indicated that the free fatty acid content increased from the initial stage in all packaging treatments, with no significant differences observed up to 4 months. However, after 6 months of storage, significant differences were observed at a 99% confidence level. The highest free fatty acid content was observed in PP (-0.06 MPa) at 0.610%, which was not statistically different from PP (-0.04 MPa) and PP (-0.02 MPa), with values of 0.595% and 0.588%, respectively. Conversely, the lowest free fatty acid content was found in woven plastic bags at 0.435%, but this was not statistically different from PP (-0.08 MPa), which had a value of 0.503%, or PP (-0.02 MPa) at 0.505%. The study assessed the effects of different storage conditions on free fatty acid content in peanut seeds. The results showed that there were no statistically significant differences in free fatty acid content between 0 and 2 months of storage. However, significant differences, with a 99% confidence level, were observed at 4 and 6 months. The highest free fatty acid content was recorded in ambient conditions at 0.494% and 0.664% for 4 and 6 months, respectively. In contrast, the lowest levels of free fatty acids were found in controlled conditions at 0.385% and 0.414% for 4 and 6 months, respectively. A significant statistical interaction was observed between the packaging treatments and storage conditions for peanut seeds, except during the first 2 months. At 4 months, the highest free fatty acid content was observed in the combination of PP (-0.02 MPa) with ambient conditions, at 0.616%. However, there were no statistically significant differences when compared with PP and PP (-0.04 MPa) in combination with ambient conditions, which were at 0.553% and 0.490%, respectively. The lowest free fatty acid content was recorded in the combination of PP (-0.04 MPa) with controlled conditions, at 0.320%, followed by PP (-0.02 MPa) with controlled conditions, at 0.336%, respectively. After 6 months, the highest free fatty acid content was found in PP (-0.04 MPa) with ambient conditions, at 0.790%, but this was not statistically different from PP with ambient conditions at 0.773%, respectively. The lowest free fatty acid content among all packaging treatments was observed in the combination of controlled conditions with PP (-0.06 MPa) with ambient conditions (Table 1).

Dehydrogenase enzyme activity (OD Value)

The study investigated the effects of different packaging treatments on the dehydrogenase activity of stored peanut seeds at various time intervals. The results indicated that there were no statistically significant differences in dehydrogenase activity at 0, 4, and 6 months. However, at the 2-month mark, statistically significant differences, with a 99% confidence level, were observed. The highest dehydrogenase activity, measured at 1.356 OD value, was recorded in PP (-0.08 MPa). Nevertheless, this was not statistically different from PP (-0.06 MPa), which had a dehydrogenase activity of 1.203 OD value. After 6 months of storage, the highest dehydrogenase activity was observed in PP (-0.04 MPa), with a value of 1.155 OD. However, this was not statistically different from other packaging treatments. Regarding the effects of storage conditions, the results indicated that dehydrogenase activity was not statistically different at 0, 2, and 4 months. However, a significant difference, with a 99% confidence level, was observed at the 6-month mark. The highest dehydrogenase activity, measured at 1.124 OD value, was found in controlled conditions, while the lowest dehydrogenase activity, at 0.937 OD value, was observed in ambient conditions. No significant interaction was observed between the packaging treatments and storage conditions for peanut seeds regarding dehydrogenase activity at 0, 2, 4, and 6 months. At 2 and 4 months, the highest dehydrogenase activity was observed in the combination of PP (-0.08 MPa) with controlled conditions, with OD values of 1.410 and 1.333, respectively. At 6 months, the highest dehydrogenase activity was observed in PP (-0.04 MPa) combined with controlled conditions, with an OD value of 1.327. However, no statistically significant differences were observed when compared to other treatments for the same month. Additionally, the total dehydrogenase activity (TDH) decreased in all packaging treatments stored in ambient conditions (Table 2).

Table 1. Free fatty acids content of peanut var. Tainan 9 with different packaging treatments before and after stored in different conditions for 6 months

Factors		**Free fatty acids content**			
		Month 0	**Month 2**	**Month 4**	**Month 6**
Packaging treatment					
woven plastic bag		0.336	0.351	0.406	0.435 b
PP		0.351	0.335	0.478	0.610 a
PP (-0.02 MPa)		0.348	0.350	0.476	0.503 b
PP (-0.04 MPa)		0.333	0.340	0.405	0.588 a
PP (-0.06 MPa)		0.345	0.346	0.435	0.595 a
PP (-0.08 MPa)		0.331	0.320	0.438	0.505 b
Storage condition					
Ambient		0.356	0.369	0.494 a	0.664 a
Controlled		0.325	0.311	0.385 b	0.414 b
Packaging treatment × Storage condition					
Control	Ambient	0.336	0.390	0.396 cd	0.476 bc
	Controlled	0.336	0.313	0.416 bcd	0.393 c
PP	Ambient	0.383	0.363	0.553 ab	0.773 a
	Controlled	0.320	0.306	0.403 cd	0.446 c
PP (-0.02 MPa)	Ambient	0.363	0.373	0.616 a	0.570 b
	Controlled	0.333	0.326	0.336 d	0.436 c
PP (-0.04 MPa)	Ambient	0.333	0.383	0.490 abc	0.790 a
	Controlled	0.333	0.296	0.320 d	0.386 c
PP (-0.06 MPa)	Ambient	0.396	0.383	0.463 bcd	0.793 c
	Controlled	0.293	0.310	0.406 cd	0.396 c
PP (-0.08 MPa)	Ambient	0.326	0.323	0.446 bcd	0.583 b
	Controlled	0.336	0.316	0.430 bcd	0.426 c
F-test					
Packaging treatment		ns	ns	ns	**
Storage condition		ns	ns	**	**
Packaging treatment × Storage condition		ns	ns	*	**
C.V. (%)		58.32	26.51	17.24	11.54

ns: not significantly different, * and ** significantly different at 95% and 99% levels.

[1]/Different uppercase letters in same vertical are significantly different by method of Ducan's New Multiple Range Test (DMRT).

Table 2. Dehydrogenase enzyme activity of peanut var. Tainan 9 with different packaging treatments before and after stored in different conditions for 6 months

Factors		Dehydrogenase enzyme Activity (OD Value)			
		Month 0	Month 2	Month 4	Month 6
Packaging treatment					
woven plastic bag		1.126	1.014 c	1.060	1.003
PP		1.052	1.017 c	1.037	0.968
PP (-0.02 MPa)		1.073	0.998 c	1.041	0.940
PP (-0.04 MPa)		1.019	1.046 bc	0.963	1.155
PP (-0.06 MPa)		1.034	1.203 ab	1.062	1.042
PP (-0.08 MPa)		1.108	1.356 a	1.261	1.076
Storage condition					
Ambient		1.111	1.097	1.033	0.937 b
Controlled		1.027	1.114	1.108	1.124 a
Packaging treatment × Storage condition					
Control	Ambient	1.196	1.024	1.013	0.970
	Controlled	1.057	1.003	1.108	1.035
PP	Ambient	1.103	0.980	1.025	0.885
	Controlled	1.001	1.054	1.050	1.050
PP (-0.02 MPa)	Ambient	1.080	0.992	1.022	0.838
	Controlled	1.066	1.004	1.059	1.042
PP (-0.04 MPa)	Ambient	1.034	1.019	0.920	0.984
	Controlled	1.004	1.073	1.006	1.327
PP (-0.06 MPa)	Ambient	1.064	1.264	1.028	0.913
	Controlled	1.004	1.142	1.095	1.171
PP (-0.08 MPa)	Ambient	1.187	1.302	1.190	1.034
	Controlled	1.030	1.410	1.333	1.119
F-test					
Packaging treatment		ns	**	ns	ns
Storage condition		ns	ns	ns	**
Packaging treatment × Storage condition		ns	ns	ns	ns
C.V. (%)		16.681	12.705	14.762	16.698

ns: not significantly different and ** significantly different at 99% levels.
[1]/Different uppercase letters in same vertical are significantly different by method of Ducan's New Multiple Range Test (DMRT).

Seed moisture content

The study examined the influence of different packaging treatments on the moisture content of stored peanut seeds. The observations on the moisture content of peanut seeds were significantly different at the 99% confidence level from 2 to 6 months of storage, except at the initial stage. At 2, 4, and 6 months of storage, seeds stored in woven plastic bags recorded the lowest moisture content for all the months, which were 5.28%, 5.23%, and 5.10%, respectively. However, the moisture content for each month was nearly similar when compared to the initial stage. Regarding the moisture content under different storage conditions, significant differences were observed at the 99% confidence level at 2, 4, and 6 months of storage. The highest moisture content was recorded in controlled conditions, at 5.88%, 5.79%, and 5.89% for 2, 4, and 6 months, respectively. Conversely, the lowest moisture content was observed in ambient conditions, which measured 5.67%, 5.49%, and 5.49%, respectively. A significant statistical interaction between packaging materials and storage conditions for peanut seeds was observed at 4 months of storage, except at 0, 2, and 6 months. At 4 months, the highest moisture content was found in the combination of PP (-0.02 MPa) with controlled conditions, at 5.92%. However, this was not statistically different from PP (-0.04 MPa) and PP in combination with controlled conditions, which measured 5.91% and 5.89%, respectively. Conversely, the lowest moisture content was observed in woven plastic bags combined with ambient conditions, at 4.87% (Table 3).

Table 3. Seed moisture content of peanut var. Tainan 9 with different packaging treatments before and after stored in different conditions for 6 months

Factors		**Seed moisture content (%)**			
		Month 0	**Month 2**	**Month 4**	**Month 6**
Packaging treatment					
woven plastic bag		5.75	5.28 c	5.23 b	5.10 b
PP		5.83	5.72 b	5.67 a	5.80 a
PP (-0.02 MPa)		5.63	5.90 ab	5.76 a	5.71 a
PP (-0.04 MPa)		5.84	5.78 ab	5.78 a	5.88 a
PP (-0.06 MPa)		5.96	5.99 a	5.63 a	5.71 a
PP (-0.08 MPa)		6.24	5.97 a	5.77 a	5.92 a
Storage condition					
Ambient		5.95	5.67 b	5.49 b	5.49 b
Controlled		5.81	5.88 a	5.79 a	5.89 a
Packaging treatment × Storage condition					
Control	Ambient	5.78	5.06	4.87 d	4.79
	Controlled	5.72	5.49	5.60 bc	5.41
PP	Ambient	5.80	5.70	5.44 c	5.66
	Controlled	5.86	5.74	5.89 a	5.93
PP (-0.02 MPa)	Ambient	5.70	5.85	5.60 bc	5.52
	Controlled	5.57	5.95	5.92 a	5.90
PP (-0.04 MPa)	Ambient	5.74	5.59	5.66 abc	5.76
	Controlled	5.95	5.98	5.91 a	5.99
PP (-0.06 MPa)	Ambient	6.04	5.84	5.60 bc	5.38
	Controlled	5.88	6.14	5.65 abc	6.04
PP (-0.08 MPa)	Ambient	6.61	5.98	5.77 ab	5.81
	Controlled	5.87	5.97	5.77 ab	6.04
F-test					
Packaging treatment		ns	**	**	**
Storage condition		ns	**	**	**
Packaging treatment × Storage condition		ns	ns	**	ns
C.V. (%)		6.82	2.86	2.62	3.73

ns: not significantly different and ** significantly different at 99% levels.
[1]/Different uppercase letters in same vertical are significantly different by method of Ducan's New Multiple Range Test (DMRT).

Seed water activity

The water activity in peanut seeds was measured using an RR moisture analyzer. Peanut seeds stored with different packaging treatments showed significant differences at a 99% confidence level after 0 to 6 months of storage. At 0, 2, 4, and 6 months, peanut seeds stored in woven plastic bags recorded the lowest water activities, measuring 0.672, 0.609, 0.550, and 0.556, respectively. The effects of storage conditions were found to be significantly different at a 95% confidence level at the initial stage and statistically different at a 99% confidence level at 2, 4, and 6 months. From 0 to 6 months, the highest water activities under controlled conditions were 0.680, 0.660, 0.635, and 0.636, while the lowest water activities at ambient conditions were 0.677, 0.646, 0.597, and 0.610, respectively. However, there was no significant difference when compared with the initial water activity value. A significant statistical interaction between packaging treatments and the storage conditions of peanut seeds was observed at 0, 4, and 6 months, except at 2 months. At 0, 4, and 6 months, the lowest water activity was observed in woven plastic bags combined with ambient conditions, measuring 0.666, 0.494, and 0.529, respectively (Table 4).

Germination percentage

The study examined the effects of different packaging treatments on the germination percentage of peanut seeds. The results indicated that the germination percentage declined as the storage period advanced, but no significant changes were recorded throughout the 0 to 6 months of storage. Germination decreased in all packaging treatments. The overall ranking of germination percentages in peanuts with different packaging treatments was as follows, in decreasing order: PP (-0.08 MPa), PP (-0.06 MPa), woven plastic bag, PP, PP (-0.02 MPa), and PP (-0.04 MPa), with values of 53.33%, 57.33%, 59.33%, 61.33%, 62.33%, and 62.33%, respectively. Regarding the influence of different storage conditions on the germination percentage of peanut seeds, the results showed no significant differences at 0 to 2 months. However, a statistically significant difference of 99% was observed at 4 and 6 months of storage. The highest germination percentages were recorded in controlled conditions, at 78.88% and 76.44% for 4 and 6 months, respectively, while the lowest germination percentages were observed in ambient conditions, at 61.55% and 42.22%, respectively. No interaction was observed between packaging treatments and storage conditions on germination percentage at 0, 2, and 4 months of storage. However, a significant statistical interaction between packaging materials and storage conditions on germination percentage was observed at 6 months. The seeds treated with PP (-0.04 MPa) in combination with controlled conditions recorded the highest germination percentage of 82.66%, followed by PP (-0.06 MPa) in combination with controlled conditions at 80.66%. Nevertheless, there was no statistical difference when compared with all packaging treatments stored in controlled conditions, except for woven plastic bags (Table 5).

Table 4. Seed water activity of peanut var. Tainan 9 with different packaging treatments before and after stored in different conditions for 6 months

Factors		**Seed water activity**			
		Month 0	**Month 2**	**Month 4**	**Month 6**
Packaging treatment					
woven plastic bag		0.672 c	0.609 d	0.550 e	0.556 b
PP		0.681 a	0.670 a	0.636 b	0.631 a
PP (-0.02 MPa)		0.680 a	0.664 ab	0.670 a	0.630 a
PP (-0.04 MPa)		0.678 ab	0.652 c	0.646 b	0.635 a
PP (-0.06 MPa)		0.676 b	0.666 ab	0.616 c	0.645 a
PP (-0.08 MPa)		0.682 a	0.658 bc	0.577 d	0.642 a
Storage condition					
Ambient		0.677 b	0.646 b	0.597 b	0.610 b
Controlled		0.680 a	0.660 a	0.635 a	0.636 a
Packaging treatment × Storage condition					
Control	Ambient	0.666 d	0.598	0.494 g	0.529 f
	Controlled	0.678 bc	0.620	0.607 de	0.582 e
PP	Ambient	0.683 a	0.665	0.609 de	0.627 cd
	Controlled	0.678 abc	0.674	0.663 b	0.636 abc
PP (-0.02 MPa)	Ambient	0.678 abc	0.659	0.646 bc	0.608 d
	Controlled	0.682 ab	0.669	0.694 a	0.653 a
PP (-0.04 MPa)	Ambient	0.677 bc	0.651	0.649 bc	0.630 bc
	Controlled	0.680 abc	0.652	0.643 bc	0.641 abc
PP (-0.06 MPa)	Ambient	0.676 c	0.658	0.626 cd	0.634 abc
	Controlled	0.676 c	0.675	0.605 de	0.656 a
PP (-0.08 MPa)	Ambient	0.680 abc	0.647	0.558 f	0.634 abc
	Controlled	0.684 a	0.669	0.595 e	0.650 ab
F-test					
Packaging treatment		**	**	**	**
Storage condition		*	**	**	**
Packaging treatment × Storage condition		**	ns	**	*
C.V. (%)		0.43	1.19	2.12	1.88

ns: not significantly different, * and ** significantly different at 95% and 99% levels.

[1]/Different uppercase letters in same vertical are significantly different by method of Ducan's New Multiple Range Test (DMRT).

Table 5. Germination percentage of peanut var. Tainan 9 with different packaging treatments before and after stored in different conditions for 6 months

Factors		Germination (%)			
		Month 0	Month 2	Month 4	Month 6
Packaging treatment					
woven plastic bag		95.33	81.33	69.66	59.33
PP		90.66	78.00	75.00	61.33
PP (-0.02 MPa)		94.33	80.00	65.00	62.33
PP (-0.04 MPa)		91.00	79.66	68.66	62.33
PP (-0.06 MPa)		94.33	79.33	71.00	57.33
PP (-0.08 MPa)		92.00	82.33	72.00	53.33
Storage condition					
Ambient		93.77	79.11	61.55b	42.22 b
Controlled		92.11	81.11	78.88a	76.44 a
Packaging treatment × Storage condition					
Control	Ambient	95.33	78.66	64.00	52.00 c
	Controlled	95.33	84.00	75.33	52.00 b
PP	Ambient	94.00	79.33	68.66	43.33 cd
	Controlled	87.33	76.66	81.33	79.33 ab
PP (-0.02 MPa)	Ambient	94.00	78.00	52.66	45.33 cd
	Controlled	94.66	82.00	77.33	79.33 ab
PP (-0.04 MPa)	Ambient	94.66	80.66	60.66	42.00 cd
	Controlled	87.33	78.66	76.66	82.66 a
PP (-0.06 MPa)	Ambient	93.33	76.00	61.33	34.00 d
	Controlled	95.33	82.66	80.66	80.66 a
PP (-0.08 MPa)	Ambient	91.33	82.00	62.00	36.66 d
	Controlled	92.66	82.66	82.00	70.00 ab
F-test					
Packaging treatment		ns	ns	ns	ns
Storage condition		ns	ns	**	**
Packaging treatment × Storage condition		ns	ns	ns	*
C.V. (%)		4.74	5.95	8.30	11.98

ns: not significantly different, * and ** significantly different at 95% and 99% levels.
[1]/Different uppercase letters in same vertical are significantly different by method of Ducan's New Multiple Range Test (DMRT).

Germination index

The study assessed the effects of different packaging treatments on the germination index of peanut seeds, and no significant changes were observed throughout the storage period from 0 to 6 months. In the germination index, a decrease was noted in all packaging treatments. The overall ranking of the germination index for peanuts in different containers was as follows, in decreasing order: PP (-0.08 MPa), PP (-0.06 MPa), woven plastic bag, PP, PP (-0.02 MPa), and PP (-0.04 MPa), with values of 2.66%, 2.86%, 2.96%, 3.06%, 3.11%, and 3.11%, respectively. Regarding the influence of different storage conditions on the germination index of peanut seeds, there were no statistically significant differences at 0 and 2 months. However, at 4 and 6 months, a statistically significant difference of 99% was observed. The highest germination index was recorded in controlled conditions, at 3.94% and 3.82% for 4 and 6 months, respectively, while the lowest germination index was observed in ambient conditions, at 2.96% and 2.11%, respectively. No interaction was observed between packaging treatments and storage conditions on the germination index at 0, 2, and 4 months. However, a significant statistical interaction was observed after 6 months of storage. The seeds treated with PP (-0.04 MPa) in combination with controlled conditions recorded the highest germination index of 4.13%, followed by PP (-0.06 MPa) in combination with controlled conditions at 4.03%. Nevertheless, there was no statistical difference when compared with all packaging treatments stored in controlled conditions, except for woven plastic bags (Table 6).

Table 6. Germination index of peanut var. Tainan 9 with different packaging treatments before and after stored in different conditions for 6 months

Factors		**Germination index**			
		Month 0	**Month 2**	**Month 4**	**Month 6**
Packaging treatment					
woven plastic bag		4.76	4.06	3.41	2.96
PP		4.53	3.90	3.65	3.06
PP (-0.02 MPa)		4.71	4.00	3.25	3.11
PP (-0.04 MPa)		4.55	3.98	3.41	3.11
PP (-0.06 MPa)		4.71	3.90	3.38	2.86
PP (-0.08 MPa)		4.60	4.08	3.60	2.66
Storage condition					
Ambient		4.68	3.93	2.96 b	2.11 b
Controlled		4.60	4.04	3.94 a	3.82 a
Packaging treatment × Storage condition					
Control	Ambient	4.76	3.93	3.06	2.60 c
	Controlled	4.76	4.20	3.76	3.33 b
PP	Ambient	4.70	3.96	3.23	2.16 cd
	Controlled	4.36	3.83	4.06	3.96 ab
PP (-0.02 MPa)	Ambient	4.70	3.90	2.63	2.26 cd
	Controlled	4.73	4.10	3.86	3.96 ab
PP (-0.04 MPa)	Ambient	4.73	4.03	3.00	2.10 cd
	Controlled	4.36	3.93	3.83	4.13 a
PP (-0.06 MPa)	Ambient	4.66	3.66	2.73	1.70 d
	Controlled	4.76	4.13	4.03	4.03 a
PP (-0.08 MPa)	Ambient	4.56	4.10	3.10	1.83 d
	Controlled	4.63	4.06	4.10	3.50 ab
F-test					
Packaging treatment		ns	ns	ns	ns
Storage condition		ns	ns	**	**
Packaging treatment × Storage condition		ns	ns	ns	*
C.V. (%)		4.74	6.29	9.34	11.98

ns: not significantly different, * and ** significantly different at 95% and 99% levels.
[1]/Different uppercase letters in same vertical are significantly different by method of Ducan's New Multiple Range Test (DMRT).

Discussion

Peanut seeds often suffer from oxidation and moisture fluctuations during storage. The quality of peanut seeds decreases as the storage period increases. Seeds lose their germination and viability, and vacuum packaging can be used to extend their shelf life because seeds are essential raw materials in agriculture. Therefore, seed viability and vigor must be maintained (Anjian *et al*., 2016; Meena *et al*., 2020). Packaging and packaging types have a direct influence on physical and chemical changes. In general, the most widely used packaging material is plastic due to its light weight, good product quality, ability to determine the shape of the packaging, and recyclability (Narayanan and Dordi, 1998). Peanut seed quality deterioration increases with the advancement of the storage period. Factors such as dehydrogenase activity, seedling vigor index, germination percentage, seed infection, and moisture content increase over time. However, when peanuts are stored in polyethylene 700-gauge packaging, seed quality is better maintained even after 10 months of storage (Vasudevan *et al.,* 2014). Sheik *et al*. (1985) reported that vacuum and nitrogen gas replacement in the packaging of peanuts inhibited rancidity and fungal growth. In this study, packaging treatments affected the percentage of free fatty acids, which increased during the 4 to 6 months of storage. The germination percentage and germination index decreased throughout the increasing storage period, while dehydrogenase enzyme activity, moisture content, and water activity remained close to their initial values. The most suitable packaging treatments for Tainan 9 peanut seeds were PP (-0.04 MPa), followed by PP (-0.06 MPa), as they were the best at maintaining quality. Dehydrogenase activity, germination, and germination index were the highest, while free fatty acids were the lowest. This is consistent with Anjian *et al*. (2016) who reported that vacuum packaging at a pressure of -0.06 MPa was the most suitable for preserving peanut quality.

Storage conditions are crucial for maintaining the quality of peanut seeds. Due to their high oil content, the deterioration of peanut seeds depends on the postharvest storage conditions, including relative humidity and temperature in the atmosphere, which generally influence seed longevity (Meena *et al*., 2020). The storage conditions of peanut seeds affected several factors during storage. These include an increase in free fatty acids, a decrease in dehydrogenase enzyme activity, germination percentage, and germination index in ambient conditions. Moisture content and water activity of peanuts under ambient conditions had the lowest values but were not significantly different from the initial values. The most efficient packaging treatments for Tainan 9 peanut seeds were controlled conditions (13 ± 2°C, 19 ± 11% RH), as they were the most effective in maintaining quality. Dehydrogenase activity, germination, and germination index were the highest, while free fatty acids were the lowest. This aligns with the findings of Koskosidis *et al*. (2022), who reported that storing soybeans in cold conditions preserved quality better than at room temperature. Storage of peanut seeds at relatively low temperatures and high relative humidity can also affect peanut quality. For example, peanut kernels stored at 19°C and 64% relative humidity had the highest moisture content and the largest physical damage, while samples stored at 24°C and 56% relative humidity had the lowest moisture content, physical damage, and rancidity (Mutegi *et al*., 2013). Consistent with these findings, peanut kernels stored hermetically at room temperature (23-25°C) with low humidity (below 4%) maintained high germination rates (>85%) for up to 8 years (Rao *et al*., 2002). Additionally, Liu *et al*. (2022) reported that storing peanuts at 15°C for 160 days maintained the protein composition and structure of peanuts. Similarly, Liu *et al*. (2019) found that peanut seeds stored at 15°C or subjected to short-term storage at 25°C were suitable options. Temperature during storage can significantly impact lipid levels and peanut oxidation, with higher temperatures leading to increased lipid oxidation and nutrient loss.

In general, seeds stored in moisture-proof containers retain better quality compared to moisture-permeable containers under ambient and cold conditions. This is because seed moisture fluctuates more in a moisture-permeable container than in a moisture-proof container (Meena *et al*., 2020). This finding is consistent with the report by Bhattacharya and Raha (2002), who stated that hulled peanut seeds with a moisture content of not more than 6% can be stored for at least 10 years without a loss of germination when stored in a sealed container at temperatures slightly above freezing (2 to 5 °C). Different packaging methods can maintain the quality of peanuts for varying periods of storage. Therefore, choosing an appropriate container for storing peanut seeds is essential and should be determined based on the desired storage period and desired quality (Fu *et al*., 2018). The choice of packaging treatment combined with storage conditions affects the percentages of free fatty acids, dehydrogenase enzyme activity, germination percentage, and germination index. There is a reduction in all packaging treatments when combined with ambient conditions. Meanwhile, the moisture content and water activity in the woven plastic bag packaging combined with ambient conditions are the lowest. This experiment demonstrated that the most suitable packaging treatment and storage conditions for the peanut variety Tainan 9 were polypropylene 760 gauge (-0.04 MPa) combined with controlled conditions, followed by PP (-0.06 MPa) combined with controlled conditions. These treatments were the most effective in maintaining quality for 6 months throughout the storage period, resulting in the highest dehydrogenase activity, germination percentage, and germination index, while free fatty acids were the lowest.

Acknowledgements

We would like to express our gratitude to the King Mongkut's Institute of Technology Ladkrabang (Grant number 2566-02-04-015) for their financial support of this research. Additionally, we extend our thanks to School of Agricultural Technology, King Mongkut's Institute of Technology Ladkrabang, Thailand, for their support in providing the research site.

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(Received: 28 September 2023, Revised: 21 December 2023, Accepted: 1 January 2024)