



## POST-HARVEST NUTRIENT RETENTION AND DEGRADATION IN MUSTARD SEEDS AND LEAVES

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### Abstract

Mustard (*Brassica juncea* L. and its relatives) is a significant world crop, both for oilseed and leafy vegetable production and in terms of the nutritional value of its seeds and leaves for oil, protein, ascorbic acid, carotenoids, minerals and bioactive compounds derived from glucosinolate. Chemical instability is associated with major losses of nutrients between harvest and consumption/processing, and this is related to shelf life. The present systematic review attracts literature published from 2021 to 2026 by the PRISMA informed search and screening strategies (Page et al, 2021) related to nutrient retention and degradation of mustard seeds and leaves. Twenty-eight studies were selected for the qualitative synthesis, based on the inclusion criteria. The results reveal that moisture content and storage temperature are the most important factors affecting seed losses while ascorbic acid oxidation, degradation of chlorophyll, and glucosinolates degradation through myrosinase activity are the dominant factors responsible for losses in leaf and microgreen stage. All of the post-harvest treatment/technologies, including modified atmosphere packaging (MAP), coloured light filtering bag, low temperature storage, hermetic seed bagging and optimum drying and blanching sequence treatments were consistently associated with better preservation of plant nutrients as compared to ambient or uncontrolled handling. The review highlights the loophole/mega problem in the uniqueness of post-harvest data for mustard in comparison to the other members of the Brassica group and the requirement for low-tech, cost-effective solutions for India as the losses are widespread and are extensive. Agronomic implications for the smallholders, food-grade mustard seeds storage and value-added processing of mustard greens are discussed.

**Keywords:** *Brassica juncea*, postharvest physiology, nutrient degradation, glucosinolates, ascorbic acid, seed storage, agronomy

### 1. Introduction

Mustard; *Brassica juncea* (L.) C. (Czern.) is one of the most popular oilseed-cum-vegetable crops of the Indian subcontinent, China and some parts of Europe, which is well known for its seed oil, proteinous meal and young, aromatic leaves as leafy green in South Asian, East Asian and African foods (Hu & Yan, 2025). Agronomically, it is an early maturing crop that can be grown on marginal and semi-arid soils and requiring balanced macro- and micronutrients management, is important option for the smallholders during the rabi-season (Sharma et al., 2025). The agronomic research in the recent past has improved sowing practices, sulfur and boron nutrition, mulching techniques to increase the actual yield and its intrinsic oil and protein quality of the crop at harvest (Dhaliwal et al., 2022; Sharma et al., 2025).

Mustard is also of great nutritional importance throughout its two growth stages reviewed in this review. The oil content of mature seed is around 28–32% (dry-weight basis) with a high level of

fatty acids such as oleic acid, linoleic acid, linolenic acid and erucic acid (Haque et al., 2025). However, the leaf is a rich source of ascorbic acid,  $\beta$ -carotene, calcium, iron and phosphorus; and the youngest stage of micro-growth has even higher levels of these constituents compared to the mature green (Das & Dhar, 2023; Kyriacou et al., 2021). “Sinigrin, the predominant glucosinolate in tissues, further requires hydrolysis by myrosinase to release isothiocyanate which has antimicrobial and chemo preventive bioactivities (Abdel-Massih et al., 2023; Hu & Yan, 2025).

The nutritional value, however, which is already present at the harvest stage is not ensured along the chain automatically. India is estimated to have losses in the range of hundreds of billions of rupees, on the harvest and post-harvest for all major categories of agricultural commodities, with fruits and vegetables being the highest loss category (Statista, 2023). These losses are identified as mostly structural rather than systemic, involving weak cold-chain infrastructure, transportation issues, inadequate on-farm drying and storage facilities, and on-going farm-level policy analysis promoting policies as a cost-effective pathway to mitigate produce and grain losses (Gulati et al., 2024). The two pathways of loss are different in a crop such as mustard used as a seed and the very perishable leafy vegetable, and hence different post-harvest strategies should be employed.

Dry seed undergoes the main degradative pathways of oxidative rancidity of unsaturated lipids, free-radical mediated membrane damage and the loss of germinal vigour which occurs with prolonged exposure to elevated moisture, temperature and oxygen concentration (Nadarajan et al., 2023). Most of the degradation of the fresh leaf and micro-green tissues happens via ascorbate oxidation, chlorine degradation and glucosinolate hydrolysis by myrosinase, which are triggered by mechanical injury, high storage temperature, and water loss (Lin et al., 2021). The biochemical deterioration of the seed and leaf are quite independent and therefore must be considered separately in the context of mustard post-harvest physiology, but common agronomic and handling implications must be learnt.

While much has been done in horticultural Brassica crops like broccoli, cabbage and kale to study postharvest physiology, the available data for mustard are relatively scattered in agronomy, food-science and postharvest-technology journals and in many cases mustard is included in general “Brassica vegetable”. However, literature based on postharvest physiology of mustard crop (mustard) is fairly nebulous and in many instances merged in the general group of “Brassica vegetable” in journals relating to agronomy and food-science and postharvest-technology. To synthesize literature of the nutrient outcomes from a defined postharvest application scenario of mustard (Brassica juncea, Brassica nigra and/or Sinapi's alba) seeds and/or leaves, the following search-and-screening logic as recommended in PRISMA 2020 (Page et al., 2021) was structured in a systematic review. The review first summarizes the nutrient profile at harvest then considers separately the degradation pathways of the nutrients found in the seed and in the leaf/microgreen tissue, and lastly the technologies available for postharvest degradation which have been shown to slow degradation, such as packaging, temperature control, drying, and blanching.

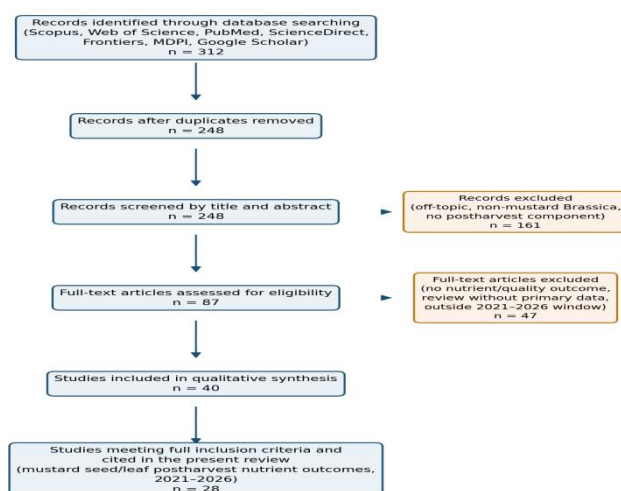
## **2. Methodology**

The articles were searched from the structured database of several platforms such as Scopus, Web of Science, PubMed / PubMed Central, Science direct, Frontiers, and MDPI journals and Google Scholar databases from January 2021 to June 2026. In the search terms, crop descriptors were used as the main terms, and the terms related to the postharvest and nutrients were included with the same sort of operators suggested by PRISMA 2020 search-reporting (Page et al., 2021).

Studies included: English-language peer-reviewed research articles, systematic review articles or institutional technical reports published from 2021–2026, reporting a measured nutrient, biochemical, sensory or post storage viability response of mustard seed or mustard leaf/microgreen tissue to one or more identified post production/processing condition (e.g., storage temp, storage atmosphere, drying method, blanching treatment, storage time). Only studies reporting results

relevant to the postharvest interpretation (e.g., seed-quality results) were retained if they only studied the effects of pre-harvest agronomic management (fertilisation, irrigation, cultivar selection) (e.g., Dhaliwal et al., 2022; Sharma et al., 2025). Only if the study of a Brassica vegetable other than mustard was part of a study that also included comparative data with an accession of mustard, or was part of a methodological or mechanistic study relevant to mustard (e.g. generic glucosinolate chemistry for hydrolysis) were studies excluded.

The records were scanned, both by abstract and title and later full-text, in accordance with the above criteria. This process ended with the identification, screening and assessment of eligibility of records and the final inclusion as per Figure 1 below (PRISMA-style flow). In this review, a total of twenty-eight studies satisfies the inclusion criteria; a few seminal studies from the history of the study of seed physiology or extension service outside this very limited timeframe (5 years) are cited for background information only and marked as such.



**Figure 1. PRISMA-style flow diagram of the literature search and study-selection process used in this systematic review (adapted from Page et al., 2021).**

If reported, the following data was collected from each study included: Crop tissue (seed, leaf, or microgreen); post-harvest treatment or storage condition; length of time; direction of the change; and approximate size of the change (for the nutrient or quality of parameter of interest). Given that the studies in the sample varied in study design, cultivars included, and analysis method, a narrative (qualitative) synthesis was used, which was recommended for synthesis for studies that were heterogeneous in effects (Page et al., 2021).

### 3. Results

#### 3.1 Nutrient Profile at Harvest

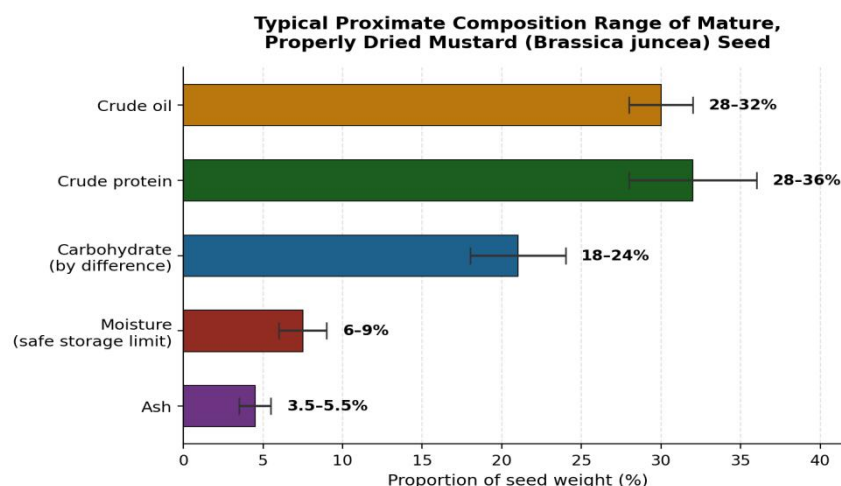
Mustard seed is at its highest oil and protein content at physiological maturity, and is reported to contain between about 28-32% crude oil and 28-36% crude protein on a dry-weight basis, with carbohydrates ranging from 18-24% and ash content from 3.5-5.5% (Haque et al. 2025). These typical proximate ranges are summarised in Figure 4 (which is presented for convenience here to the reader), as well as the recommended safe storage moisture (about 9%) below which enzymatic and microbial deterioration during storage will be significantly reduced.

The dominant fatty acid found in the seed oil is oleic, followed by linoleic, linolenic and erucic acid, which increased in number in the improved cultivars compared to the traditional cultivars, and also varied in terms of iodine value and storage stability of the oil from the mustard cultivar due to the presence of these acids which are susceptible to rapid oxidation during storage (Haque et al., 2025).

Extraction process, specifically cold pressing method has been found to produce an oil with high oxidative stability during storage period of 60 days as compared to hot pressing method, which has the oil heated for a short time at the beginning of the extraction process before the start of the storage period (Haque et al., 2025; Kabutey et al., 2023).

Mustard leaf tissue has a strong nutrient signature and is stage dependent. Mustard greens harvested at the microgreen stage had higher iron, phosphorus, calcium, ascorbic acid, and  $\beta$ -carotene levels compared to those harvested at the baby/greened and mature green stages with ascorbic acid being more than double that of the mature green stage (Das & Dhar, 2023). This nutrient density at each growing stage is consistent with the overall microgreen growth literature, which suggests a continuous increase in vitamins, minerals and phytochemicals in immature microgreen leaves relative to those of the mature vegetable (Kaya & Yardimci, 2025); and with the application of deliberate nutrient tissue manipulation through nutrient limitation in the pre-harvest stage for the preferential accumulation of beneficial phytochemicals compared to anti-nutrients like nitrate in microgreens (Kyriacou et al., 2021).

They are present in both the tissues and the seed, and one of the nutritional benefits of the crop is the bioactivity of these glucosinolates, which is dependent on the enzymatic hydrolysis to isothiocyanate, instead of the intact glucosinolate molecule (Abdel-Massih et al., 2023; Hu & Yan, 2025). This intolerance of mechanical and thermal operations during postharvest handling is the main reason why this quality (glucosinolate related quality) is particularly sensitive and will be revisited in Section 3.3.3, whereas the many other quality parameters are not.



**Figure 4. Reported proximate composition ranges for mature mustard seed and the recommended safe-storage moisture ceiling. Data sources: varietal compilation citing Sharif et al. (2017); Haque et al. (2025); Government of Saskatchewan Ministry of Agriculture mustard storage guidance.**

## 3.2 Postharvest Degradation in Mustard Seeds

### 3.2.1 Oil and Fatty Acid Quality During Storage

Mustard seed has a high moisture content in the oil-portion, which is about 50% of the seed, and thus a low safe storage moisture content is required as compared to cereal grains of similar appearance (Government of Saskatchewan Ministry of Agriculture, n.d.). However, if the temperature in the seed bin is above this, the seed will go into a post bined “sweating” process because of continued respiration, allowing moisture and heat to increase that may result in deterioration to the seed in much the same way as drying was supposed to prevent. (Government of Saskatchewan Ministry of Agriculture, n.d.).

Acid value of these storage conditions was higher in both improved (BINA) and local Bangladeshi mustard cultivars and the increase rate was highest in the hot-pressed oil stored at ambient temperature, whereas the cold-pressed oil had more favourable oxidative profile during the storage period (Haque et al., 2025). It was observed that cultivars differed significantly with respect to iodine value, which is a proxy parameter of unsaturation and hence the potential risk of oxidative shelf-life of oil, one cultivar with higher oil content recorded higher iodine value whereas the other cultivar with lower oil content recorded lower iodine value coupled with higher seed-to-oil ratio and comparatively lower risk of oxidative shelf-life (Haque et al., 2025).

Moreover, oxidative change in fatty acids as a result of storage conditions and cost of mustard oil also adds to the economic vulnerability of mustard oil in retail supply chain where the lower cost mustard oils are blended into the mustard oils which make it difficult to determine its quality and shelf-life authenticity (Begum & Jain, 2024). The indices used to verify the integrity of quality degradation during normal storage are also used to verify the integrity of adulteration of this commodity, and are practically the same type of quality control and food-safety verification.

There is also some degree of imprinting in the pre-harvest nutrient management in regard to the ability of the seed to perform during storage and processing. A foliar nutrition experiment on Indian mustard showed that the increase in harvestable foliar crude fibre (CF), total soluble solids (TSS) and seed protein content were associated with alteration in the omega-3 fatty acids (OMEGA-3) compositions of mustard oil extracted from the seeds, indicating pre-harvest effect on the oil quality trajectory post-harvest (Dhaliwal et al., 2022).

### ***3.2.2 Seed Viability, Vigour, and Biochemical Deterioration During Storage***

Seed-longevity studies conceptualize postharvest deterioration of seeds as a continuous, largely irreversible ageing process that is controlled by both moisture content of the seed and the storage temperature as well as exposure to oxygen; so, desiccation-tolerant (“orthodox”) seeds like mustard can be stored for many years only if moisture content and temperature can be kept low (Nadarajan et al., 2023). These physiological mechanisms that help hold seeds in relief against dormancy and lower metabolism rates also contribute to higher production rates of ROS and lipid peroxidation of membranes, resulting in measurable decreases of germination percentage well before the seed begins to spoil in visible ways, at high humidity and warm temperatures (Nadarajan et al., 2023).

Moreover, accelerated ageing tests with high moisture content of seeds and high exposure temperature of 40°C confirmed that the percentage of germination reduced significantly and the quality traits of seeds decreased, including cell-membrane damage, electrolyte leakage and the activity of antioxidant protective enzymes such as catalase and ascorbate peroxidase, with the greatest decrease occurring in cell-membrane damage and electrolyte leakage for oil-rich Lamiaceae seed species (Maleki Farahani et al., 2025). Although it may seem like a tale from an alternate oilseed genus, the connection between oilseed moisture content, storage temperature and deterioration due to lipids is not specific to any one genus (Maleki Farahani et al., 2025).

Hermetic Storage Technology is the case in point of how hassled moisture damage can be intentionally avoided. For agronomically different seed such as okra, but oil-bearing vegetable seed (according to the method), hermetic bagging (with 8–10% moisture level) showed significant reduction in malondialdehyde and electrical-conductivity value, as well as significant increase in germination compared to the paper, cloth, polypropylene and jute bags after 12 months in ambient storage; whereas with 14% moisture, it had the opposite effect and reduced the seed quality by holding water which may be evaporated by seed respiration (Bakhtavar et al., 2023). The result indicated that hermetic or controlled atmosphere storage was protective only when combined with appropriate drying of the seed while it was not at all effective when using inappropriate drying.

The internationally recommended seed bank protocols for seeds are a temperature at about –20°C, an RH of 15±3% and orthodox seed accessions are expected to germinate with a rate of >85% for

seed storage period extended as much as or exceeding 100 years (Nadarajan et al., 2023). Only a few commercial mustard seed units can equal the levels of gene-bank storage; but the most important factor that can easily be transferable to mustard seed handlers, which will lead to less nutrient loss and loss in viability after harvest will be low moisture and low temperature.

### ***3.2.3 Field-Stage and Cover-Crop Nutrient Accumulation Relevant to Postharvest Outcomes***

But another line of evidence is the potential of white mustard, *Sinapi's alba*, to be a postharvest cover crop — not dissimilar to alfalfa, *Medicago sativa*, it has a window of opportunity, with respect to sowing and growth. The biomass of post-sown white mustard accumulated N, P and K in proportion to precipitation and temperature during the post-harvest period in multi-year Baltic field trials, in addition, the addition of straw to the cover crop resulted in increased nutrient accumulation in the cover crop biomass (Arlauskiene & Sarunaite, 2023).

This aspect of nutrient cycling differs from grain-seed postharvest physiology, but mustards have the potential to utilize an alternative postharvest pathway to other grains, where the biomass nutrient pool can be released to the soil and the time and rate for this release are similar to those that regulate the rate of nutrient degradation in grain-seed crop postharvest (Arlauskiene & Sarunaite 2023).

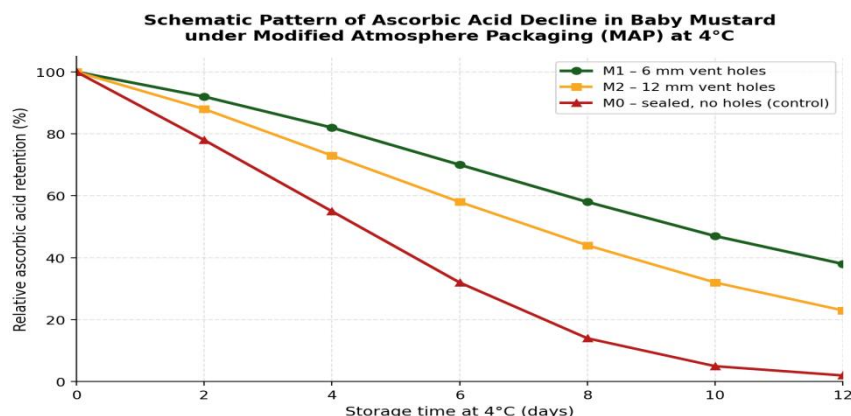
The sowing rate, quantity and quality of seeds, supplementation of sulphur and mulching among the various factors have been found effective in increasing the general vigour of sowing and producing a uniform seed lot and healthy seed lot for the post-harvest stage of rabi season sowing of Indian mustard (Sharma et al., 2025). Complementary modelling work carried out using the InfoCrop framework, and calibrated through sowing-time trials with biofertiliser and sowing-date has also found that sowing-time x biofertiliser also influences the potential yield of the crop, as well as the nutrient uptake profile (Islam et al, 2023) and thus the uniformity of the harvested crop with respect to storage moisture and consequently nutrient retention post-harvest.

## **3.3 Postharvest Degradation in Mustard Leaves and Microgreens**

### ***3.3.1 Vitamin C and Antioxidant Losses***

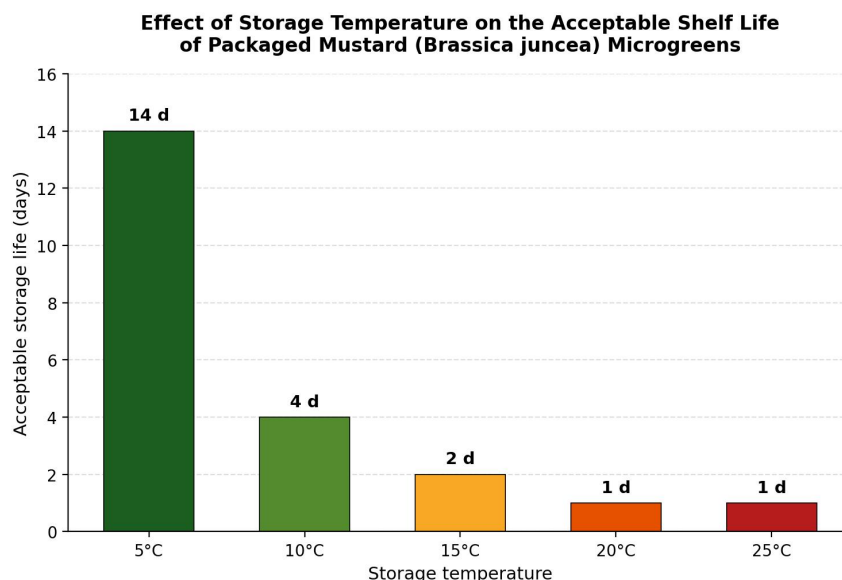
The loss of ascorbic acid from mustard leaf tissue is particularly rapid in the post-harvest period since it can be lost via non-enzymatic (ascorbate oxidase and peroxidase) and non-enzymatic processes (which increase with tissue wounding and loss of water and the rise in temperature). The ascorbic acid, total phenolics and antioxidant capacity of unwrapped baby mustard under controlled low-temperature storage (CLTS) were significantly lower than those of the baby mustard in modified atmosphere packaging (MAP) treatment, and the MAP treatment enabled the baby mustard to be stored for 3 days longer than the controlled treatment (Lin et al., 2021).

Light is another factor that influences this loss, as is packaging design. The second trial with seven different bag colours and baby mustard under light at 20°C showed that a blue bag and transparent vented bag not only extended the shelf life by 1.6 to 1.7 times longer than an unwrapped sample, but they retained the chlorophyll and carotenoids and retarded the degradation of these glucosinolates and produced the most consistent results for all quality measurement variables, which was the best treatment performed by a blue bag (Lin et al., 2022). Figure 3 is a schematic representation of comparative decrease pattern of ascorbic acid retained under similar vent versus sealed package conditions.



**Figure 3. Schematic, illustrative rendering of the comparative ascorbic-acid decline pattern described for baby mustard under three packaging treatments (not raw extracted data points). Pattern source: Lin et al. (2021).**

The influence of storage temperature on retention of antioxidants, however, is more significant than the effect of the packages design on the micro greens of mustard. In a dedicated postharvest trial, Mustard microgreens could be stored at 5°C for 14 days without significant decrease in antioxidant activity and membrane integrity while the microgreens stored at 10°C and 15°C could be stored for 4 and 2 days, respectively, without discarding beyond the detection of spoilage, whereas microgreens stored at 20°C or 25°C deteriorated beyond consumption within one day (Dayarathna et al., 2023). This is summarised in figure 2, a relationship between temperature and shelf life.



**Figure 2. Shelf life of mustard microgreens stored in 150 µm polyethylene bags at 5–25°C. Data source: Dayarathna et al. (2023).**

These temperature effects also affect, during growing and after harvest, the light conditions in which the stored product is grown. The experiments revealed a positive correlation of the photosynthetic photon flux density (ppfd) during cultivation and of postharvest storage under light conditions, compared to dark conditions, with the total amount of phenolic content at the 5-day storage period,

and overall beneficial changes in  $\alpha$ -T (and  $\beta$ -C) levels in mustard (with vital species-specific differences) as a result of postharvest light management in addition to temperature and packaging, which shows that light management during post-storage is a real control factor for antioxidant content in microgreens, not only packaging and temperature (Gudzinskaite et al., 2024).

### ***3.3.2 Chlorophyll, Carotenoids, and Visual Quality Decline***

Apart from a nutritional problem, the loss of chlorophyll in the tissues of mustard is also a commercial problem because as soon as it shows up as yellowing it indicates to the consumers that it is not fit for consumption well before reaching the biochemically critical levels of the bioactive compounds present in the mustard tissues. The low temperature Modified-atmosphere-packaging trial mentioned above showed that the higher the protection of MHT the less degradation of chlorophylls occurred and the less protected sample (unwrapped) had a higher rate of yellowing and nutrients degradation. This follow-on study with the colour-bag also found that the colour-bag group with a higher ratio of chlorophyll and carotenoid retention are the ones transmitting light in a higher ratio of blue and white light to the other colour-bag groups that change light in a less favourable ratio (Lin et al., 2022).

When the leaf tissue of mustard or other Brassica species is used to make dried or powdered ingredients, drying method is the most important factor controlling the retention of pigments. Using TBMs and drying conditions with vegetable-based by-products from Brassica species, significant differences were found in the physicochemical, functional and antioxidant properties of the resulting powders; milder TBMs and drying conditions favoured the antioxidant and pigment properties of the by-products compared to harsher drying conditions (Bas-Bellver et al., 2022).

The amount of the bioactive compounds decreased with blanching time, but paradoxically increased at the first blanching time, whereas minerals like calcium, and potassium levels increased with blanching time despite a decrease in antioxidant activity (Maila & Tseke, 2024). This up-and-down trend suggests blanching duration, more than presence or absence of blanching, is the more relevant factors when considering blanching process for leafy Brassica in general, which includes mustard greens.

### ***3.3.3 Glucosinolates and Bioactive Sulphur Compound Stability***

Myrosinase, an indigenous thioglucosidase enzyme, is regulated during post-harvest handling, is compartmentalised and only becomes active with the disruption of cell walls, as in cutting, bruising, freezing as well as long storage induced senescence and the so called mustard oil bomb defence reactions (Abdel-Massih et al., 2023).

The same packaging treatments that were effective in the prevention of ascorbic acid and chlorophyll degradation have been shown to be effective in slowing degradation of glucosinolate in baby mustard. The vented modified-atmosphere packaging trial showed that the glucosinolate reduction was less in the holed bags compared to an unwrapped control, and the colour-bag packaging trial showed that blue-bag packaging is effective at reducing the degradation of glucosinolates better than other colours of bags tested (Lin et al., 2021, 2022).

The effect of the processing method is even greater as soon as the mustard or related Brassica tissue leaves the stage of cold storage. Blanching-then-quick-freezing treatment resulted in a slightly smaller loss of measured glucosinolate content compared to blanching-then-vacuum-drying and blanching-then-oven-drying treatments; and aliphatic glucosinolates (which were more prevalent in mustard) showed higher processing stability than indolic glucosinolates (Luo et al., 2022).

In an application-oriented research study recently conducted, the importance of processing sequence in avoiding bioactive compound deactivation during processing of glucosinolates with respect to marketability was examined. A steaming fixation, rolling and vacuum freeze-drying sequence was effective in substantially retaining the health-promoting compounds and blending the resulting

mustard leaf tea with traditional green and oolong tea did not negatively impact the ability to retain these compounds and increased the sensory acceptability of the tea (Yu et al., 2025). It emphasizes the potential of the controlled heat and moisture treatment (steaming) application of the freeze-drying method as an effective process for generating value added mustard-leaf products without loss of bioactive components, an important issue for post-harvest management planning.

The undisturbed glucosinolate/isothiocyanate chemistry of mustard is not the only advantage to the postharvest process. In the last years, black mustard seed derived systems containing AITC have been tested as natural antimicrobial packaging material for the post-harvest rot of sweet cherry and found to be effective at the same level as a synthetic fungicide (Calvo et al., 2026). From the above application, it is obvious that retaining potential to retain glucosinolate-isothiocyanate pathway in mustard is beneficial to both the nutritional value of mustard and the potential input in food preservation technology after harvesting.

**3.3.4 Mineral and Macronutrient Changes in Leaf Tissue**

The mineral content of the mustard leaf tissue shows rather little variation for short periods after harvest (up to 60 days), whereas the mineral pool initially available for the retention is very sensitive to the developmental stage. During phase of development comparison mentioned above, it was found that the iron level of the mustard microgreens is approximately double that of the mature green mustard and that for phosphorus and calcium, there is also a higher concentration in microgreens compared to mature green mustard, which suggests that for the same percentage reduction in provision of the mineral, a higher amount of mineral is removed from microgreens than from mature green mustard tissue (Das & Dhar, 2023).

This mineral and phytochemical starting pool can be intentionally manipulated in a way that occurs prior to harvest even taking place. Nutrient deprivation for just 6 to 12 days before harvest using an e.g. osmotic water (OW) has been shown to lower the undesirable nitrate accumulation in microgreens of mustard, lettuce and rocket without significantly affecting the storage quality of the vegetable after harvest, thereby suggesting that the nutrient quality of the vegetable is not only determined by storage quality, but also by nutrient management in the final days before harvest (Kyriacou et al., 2021).

During longer blanching times an increase in apparent concentration was observed in the leaves, this may be related to the concentration of minerals as a result of moisture loss and changes in the structure of the plant matrix during blanching which should be taken into account when interpreting mineral information from processed mustard green (Maila & Tseke, 2024).

**3.4 Postharvest Technologies for Nutrient Retention: A Comparative Synthesis**

Table 1 consolidates the postharvest interventions examined across the studies retained in this review, organised by crop tissue, treatment category, and the principal nutrient or quality outcome reported. Read together, the evidence base points to three consistently effective intervention categories: temperature control, modified or passive atmosphere packaging, and pre-storage moisture management, each of which operates on a different point in the degradation pathways described in Sections 3.2 and 3.3.

**Table 1. Summary of Postharvest Interventions and Reported Nutrient/Quality Outcomes in Mustard (Brassica spp.) Seeds and Leaves**

| Tissue | Postharvest Intervention | Conditions Studied | Principal Nutrient / Quality Outcome | Source |
|--------|--------------------------|--------------------|--------------------------------------|--------|
|--------|--------------------------|--------------------|--------------------------------------|--------|

| Tissue                     | Postharvest Intervention                                                  | Conditions Studied                                                    | Principal Nutrient / Quality Outcome                                                                                   | Source                        |
|----------------------------|---------------------------------------------------------------------------|-----------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|-------------------------------|
| Seed                       | Cold- vs hot-pressing followed by 60-day storage                          | Ambient temperature; acid value, peroxide value, iodine value tracked | Cold-pressed oil retained a more favourable oxidative profile; hot-pressing accelerated acid-value rise                | Haque et al. (2025)           |
| Seed                       | Hermetic vs. conventional bagging (comparative oilseed/vegetable seed)    | 8–14% initial seed moisture; 12 months ambient storage                | 8–10% m.c. + hermetic bag sustained higher germination and lower MDA; 14% m.c. worsened quality even hermetically      | Bakhtavar et al. (2023)       |
| Seed                       | Accelerated ageing across moisture × duration (comparative oil-rich seed) | 5–25% seed m.c.; 24–48 h at 40°C                                      | Germination, protein content, and antioxidant-enzyme activity fell sharply as moisture and duration rose               | Maleki Farahani et al. (2025) |
| Seed                       | Foliar boron + nitrogen biofortification (pre-harvest)                    | 2-year field trial, 9 treatments                                      | Raised seed protein, crude fibre, TSS; reshaped omega-3 fatty-acid balance of extracted oil                            | Dhaliwal et al. (2022)        |
| Leaf (baby mustard)        | Modified atmosphere packaging (vented polyethylene)                       | 4°C storage; 0–12 mm vent-hole sizes                                  | Vented bags slowed ascorbic acid, phenolic, and glucosinolate decline; extended shelf life ~3 days                     | Lin et al. (2021)             |
| Leaf (baby mustard)        | Coloured, light-filtering bags                                            | 20°C with light exposure; 7 bag colours                               | Blue/transparent vented bags extended shelf life 1.6–1.7×; raised chlorophyll, carotenoid, and glucosinolate retention | Lin et al. (2022)             |
| Microgreen (mustard)       | Storage temperature                                                       | 5, 10, 15, 20, 25°C; up to 14 days                                    | 5°C maintained quality for 14 days; 25°C degraded beyond use within 1 day                                              | Dayarathna et al. (2023)      |
| Microgreen (mustard, kale) | Light intensity during cultivation and storage                            | 150–250 $\mu\text{mol m}^{-2}\text{s}^{-1}$ PPFD                      | Higher PPFD increased phenolic, $\alpha$ -tocopherol, and $\beta$ -carotene retention at day 5                         | Gudzinskaite et al. (2024)    |

| Tissue                             | Postharvest Intervention                  | Conditions Studied                                    | Principal Nutrient / Quality Outcome                                                             | Source                         |
|------------------------------------|-------------------------------------------|-------------------------------------------------------|--------------------------------------------------------------------------------------------------|--------------------------------|
| Leaf (Brassicaceae, comparative)   | Blanching + drying-method sequence        | Quick-freeze, vacuum freeze-dry, vacuum-dry, oven-dry | Blanching-then-quick-freeze best preserved glucosinolates and isothiocyanate-generating capacity | Luo et al. (2022)              |
| Leaf (purple mustard)              | Steaming + rolling + vacuum freeze-drying | 8 processing sequences compared (tea production)      | Best retention of health-promoting compounds among all sequences tested                          | Yu et al. (2025)               |
| Leaf/by-product (Brassica)         | Tissue disruption + drying condition      | Powdered-ingredient processing trial                  | Gentler disruption and lower drying temperature preserved more antioxidant and pigment content   | Bas-Bellver et al. (2022)      |
| Biomass (white mustard cover crop) | Post-harvest sowing + straw incorporation | Multi-year Baltic field trial                         | Straw incorporation increased N, P, K accumulation in post-harvest cover-crop biomass            | Arlauskiene & Sarunaite (2023) |

The attribute most consistently influenced by the storage temperature is consistently storage temperature in both materials (seed and leaf tissue). In controlled trials the shelf life of mustard microgreen was increased by reducing the storage temperature from ambient to refrigeration approximately 14 times, along with the moisture level of the samples stored (Dayarathna et al., 2023), with temperature being one of the few variables (apart from moisture) that affects the ageing reactions in orthodox-seeds (Nadarajan et al., 2023). Farmers, whether growing mustard for fresh leaf in the vegetable market or for the seed to be milled into powder or sown, will find that any slight improvement in their storage conditions with low-cost reductions in temperature will likely result in disproportionately greater benefits in terms of retaining nutrients in the product — compared to packaging or chemical treatments.

Packaging atmosphere cannot replace the lever, but it can be used with the lever. Both categories of interventions proved effective in reducing nutrient and pigment losses in baby mustard, and the two categories had a light (nutrient loss) and a respiration-gas exchange effect (pigment loss), respectively, suggesting that the two categories can operate via different mechanisms (Lin et al., 2021, 2022). Similarly, the packaging principles of mustard can be pushed outwards in relation to the use of mustard compounds in the packaging as active ingredient to protect another perishable product containing mustard active packaging agent, isothiocyanate (ISTDs) (Calvo et al., 2026).

Moisture management is implemented on two levels, on a seed level and on a leaf level – with the aid of various unit operations. The most important aspect of seed is moisture content, with pre-drying the seed to a certain moisture content prior to the storage process being the most critical; high moisture content of seeds will cause an adverse effect on seed quality even if the other aspects of the storage system are favourable (Bakhtavar et al., 2023). In comparison with the individual processes, the sequence blanching, freezing and drying is more effective in retaining the glucosinolates and pigments, while blanching-freezing and steaming-vacuum-freeze-drying sequences are better,

compared to the oven/freeze-dryer and prolonged air-drying, in the studies reviewed (Luo et al., 2022; Yu et al., 2025).

This means that investments in the reduction of postharvest losses should be made at the farm level as this prioritisation is in line with other policy level analyses relating to cost-effectiveness of postharvest losses reduction interventions in India (Gulati et al., 2024), where investment in detailed packaging technology and improved processing demonstrated the largest impact while having comparatively low costs, and where investment in establishing basic temperature control and appropriate pre-storage drying also showed large impact and comparatively low costs, has been suggested for investments in reducing the significant losses affecting mustard value chains in India.

#### **4. Discussion**

Based from the evidence gathered in this review, it can be concluded that there are two tracks conceptual models of losing nutrients during post-harvest processing of mustard. Deterioration is a gradual process in the seed tissue in which oxidative and enzymatic reactions occur, primarily in the presence of moisture and temperature and takes weeks to months, depending on the conditions, to be stopped (Nadarajan et al., 2023; Bakhtavar et al., 2023; Haque et al., 2025). Deterioration is a swift, tissue disruption- and respiration-based process which takes place within hours to days in leaf and microgreen tissue, and can be best slowed by atmosphere management and cold storage, rather than simply by moisture reduction (Lin et al., 2021; Dayarathna et al., 2023). It has important practical implications since treatments that proved successful for dry seed were not necessarily successful with fresh leaf; hermetic low oxygen storage of dry seed was found to be harmful to fresh leaf tissue (see baby mustard trials with colour bag and vented packaging, where some ventilation resulted in the best leaf-tissue packing; Lin et al., 2022).

Another cross-cutting theme is that the developmental stage of the harvest affects, but it does not impact statements made about postharvest management choices. The decisions for when a microgreen should be harvested and how much intensity the postharvest operation should be should not be made separately, since microgreen tissue is not just the most nutrient-dense among the different growth stages studied in this review, it also has the shortest postharvest stability window (Dayarathna et al., 2023; Das & Dhar, 2023; Gudzinskaite et al., 2024). This is also reflected in the fact that the nutrient pool that can be saved by postharvest nutrient treatment is not just a function of the crop genetics, but also depends on the nutrient supply to the crop during its last few days prior to harvest (Kyriacou et al., 2021), and that planning for a nutrient retention strategy must be conducted in conjunction with management of nutrients in the last few days of the crop prior to harvest.

A partial outlier to the rule of 'gentler and lower temperature handling equals better retention of nutrients' is glucosinolate-isothiocyanate chemistry. Except for a single stationary compound, the so-called bioactivity has nothing to do with it, and for a number of short, controlled thermal or mechanical procedures, such as blanching before quick-freeze freezing and steaming before freeze drying, it was shown that no significant degradation of the functional outcome occurs, and in some cases even improvement, compared with the no-treatment and prolonged low-temperature drying (Luo et al., 2022; Yu et al., 2025). Therefore, the discovery poses a question about the use of 'minimise all processing' as a post harvesting guideline for mustard as the appropriate post harvesting intervention will depend on the specific bioactive pathway that needs to be protected.

The conclusions that are currently drawn have several nuances that diminish the level of confidence: Secondly, quantitative data and information on mustard is considerably less available than similar data for other horticultural Brassica species, and several of the mechanistic insights used for this review in this study were obtained in other crops closely related to mustard, such as okra seed, cowpea leaf and Lemnaceae oilseed that are not mustard. (Maleki Farahani et al., 2025; Bakhtavar et al., 2023; Maila & Tseke, 2024). Second, although India is one of the world's important mustard producers, most of the experiments that have been carried out to answer the first question were

conducted in temperate or controlled-environment conditions, which is difficult to directly extrapolate to ambient-temperature and variable humidity conditions prevailing in mustard growing regions of India (Gulati et al, 2024). Thirdly, the agronomic input that can be made prior to harvest (such as fertigation, irrigation or cultivar) is rarely correlated with the nutrient outcome after harvest within the same experimental design; some of the studies included in this work showed measurable effects of such inputs on the nutrient pool available for postharvest retention in the first place (Dhaliwal et al., 2022; Sharma et al., 2025).

## **5. Limitations of the Review**

This review is a narrative synthesis of a wide variety of evidence which has its own set of limitations that is inherent in such a type of review. The intention to only include studies from 2021–2026 was deliberate to include the most recent postharvest-technology research, but this exclusion does not imply that an entire volume of research in seed physiology and food chemistry that is relevant to seed physiology is not. No quantitative meta-analysis attempt was made because of the extremely large cultivar number used, the diversity in growing regions, analytic approach and storage time. As a result of this, the magnitude estimates in Sections 3 and 4 are meant to be an indication of direction and approximate size and should not be interpreted as true pooled effect sizes. In some cases, close but non-mustard species had to be used as substitutes for mustard where data were unavailable for mustard, a substitution that is acceptable for biochemical pathways that are shared, such as lipid oxidation and ascorbate degradation, but is subject to uncertainty when applied to the specific mustard cultivar and tissue composition.

## **6. Conclusion**

In both cases, though, post harvesting pathways to loss of nutrition value in the mustard seed and mustard leaf/greens have been identified, well characterised and are distinct. The most consistent practice with nutrient retention, reported across the studies synthesised in this review, were the practice of reducing the storage temperature and maintaining moisture in the range of safe intakes before packing and opening the packages and the use of vented packages or packages with colour filters for modified atmosphere. The proper sequencing blanching-freezing or steaming-freeze-drying combinations of these technologies was also correlated with nutrient retention in value-added leaf products. Handling of glucosinolate related bioactivity is different from other nutrients: the initial processing steps can lead to bioactivity when performed in a short time, but this bioactivity can be preserved better by applying a more controlled set of bio-activation steps in a shorter time.

The lessons derived from the information available here are that in the context of mustard growing areas, such as India, where nutrient loss is considerable, particularly during the post-harvest activities of the agricultural produce, nutrient loss reduction through the farm and post farm-gate by temperature and moisture management is more cost-effective and should be emphasized over investment in more capital-intensive packaging or processing technology. Further research should be conducted under high temperature and variable humid field conditions in the major mustard producing areas and under experimental design to monitor pre harvest management of mustard and its relationship with the nutrient retention after harvesting, as seldom performed by researchers so far.

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