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To shatter or not to shatter: synthesizing biology and engineering for mechanised harvesting of sesame

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Abstract – Seed shattering remains a major barrier to mechanised harvesting of sesame (*Sesamum indicum* L.). It reduces yield potential, with reported losses that can exceed 50%, and hinders farmers' adoption of modern harvesting technologies. This review bridges biological and engineering disciplines by providing an integrative analysis of the genetic and morphological factors in seed retention, alongside the agronomic and mechanical strategies required for efficient harvesting. Key capsule traits, such as dehiscence angle, membrane development, and seed-placental adhesion, are examined for their roles in seed retention and suitability for mechanised harvesting. Quantitative methods for assessing shattering intensity, including the TI/KE/TO index (a score for upright retention, inverted retention, and tip opening) and Langham's capsule breakage protocol, are discussed. The review further explores advances in breeding, including the utilisation of landraces and exotic germplasm, marker-assisted selection, and identification of candidate genes and QTLs linked to shattering resistance. Mechanised harvesting methods, particularly the choice between direct and two-stage approaches, are evaluated under varying environmental conditions, with an emphasis on seed quality preservation and economic efficiency. Finally, this review is the first to propose a comprehensive ideotype framework that resolves the fundamental trade-off between field-level seed retention and mechanical threshability by systematically integrating key biological traits with engineering parameters

Keywords: Capsule shattering / capsule traits / mechanized harvesting / seed retention traits / *Sesamum indicum*

Résumé – Éclater ou ne pas éclater: synthèse des approches biologiques et d'ingénierie pour la récolte mécanisée du sésame. La déhiscence des capsules demeure un obstacle majeur à la récolte mécanisée du sésame (*Sesamum indicum* L.). Elle réduit fortement le rendement final, avec des pertes pouvant dépasser 50%, et freine l'adoption des technologies modernes de récolte par les agriculteurs. Cette revue fait le lien entre biologie et ingénierie en proposant une analyse intégrative des facteurs génétiques et morphologiques impliqués dans la rétention intra-capsulaire des graines, ainsi que des stratégies agronomiques et mécaniques nécessaires à une récolte efficace. Les principaux traits des capsules – tels que l'angle d'ouverture, le développement des membranes et l'adhérence de la graine – sont examinés pour leur rôle dans la rétention des graines et leur aptitude à la récolte mécanisée. Les méthodes quantitatives d'évaluation de l'intensité de déhiscence, notamment l'indice TI/KE/TO (score de rétention en position verticale, rétention en position inversée et ouverture de l'extrémité) ainsi que le protocole de rupture de capsule de Langham, sont discutées. La revue explore également les avancées en amélioration génétique, incluant l'utilisation de variétés locales et de ressources exotiques, la sélection assistée par marqueurs et l'identification des gènes candidats et des loci de caractères quantitatifs (QTL) associés à la résistance à la déhiscence. Les méthodes de récolte mécanisée, en particulier le choix entre une approche directe ou en deux étapes, sont évaluées selon différents contextes environnementaux, avec un accent mis sur la préservation de la qualité des graines et l'efficacité économique. Enfin, cette revue est la première à proposer un cadre idéotypique complet permettant de résoudre le compromis

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fondamental entre la rétention des graines au champ et l'adaptation au battage mécanique, en intégrant de façon systématique les principaux traits biologiques et les paramètres d'ingénierie.

Mots-clés : Déhiscence des capsules / traits de capsules / récolte mécanisée / rétention des graines / *Sesamum indicum*

Highlights

- Integrates biological and engineering approaches to address sesame harvest mechanization.
- Proposes a comprehensive ideotype framework balancing shatter resistance and threshability.
- Defines the critical trade-off between seed retention in the field and mechanical release.
- Links key capsule traits directly to optimal combine harvester settings and adjustments.
- Reviews and contextualizes quantitative methods for assessing sesame shatter resistance potential.

1. Introduction

Sesame is a strategic oilseed crop in arid and semi-arid regions, playing a critical role in food security, rural livelihoods, and climate-resilient agriculture (Hamedani *et al.*, 2022; Pathak *et al.*, 2014). Also one of the oldest domesticated oilseeds, it remains highly valued globally. Its seeds typically contain over 50% oil, characterized by a high proportion of unsaturated fatty acids (primarily oleic and linoleic acids, often >80% combined) compared to saturated fats, contributing to its reputation for cardiovascular health benefits (Gholamhoseini, 2022a). The seeds are also rich in proteins and antioxidant lignans (Ashri, 2006; Andargie *et al.*, 2021). Sesame is particularly well-suited to low-input, drought-prone farming systems, making it an essential option for sustainable agriculture in marginal environments (Dossa *et al.*, 2017a).

Despite its advantages, sesame cultivation is constrained by significant challenges, foremost among them seed shattering. The reliance on manual harvesting–a direct consequence of shattering-creates a major production bottleneck, especially as the global sesame market is projected to grow annually by nearly 5.8% (Grand View Research, 2024). Global sesame production currently exceeds 6.5 million tons annually (FAOSTAT, accessed October 25, 2025), reflecting its significant economic role. This makes shattering not only an agronomic threat through direct yield loss but also a source of substantial socioeconomic burdens, including inflated labor costs, increased farmer risk, and barriers to profitable, large-scale mechanization.

This genetically regulated dehiscence process causes substantial pre-harvest and harvest-time yield losses (Uzun *et al.*, 2002; Gholamhoseini *et al.*, 2023a). Although capsule dehiscence and seed dispersal represent beneficial natural mechanisms for seed spread, this trait poses a significant barrier to the expansion of sesame farming. As illustrated in Table 1, the largest yield losses often occur during manual harvesting of traditional, shattering-prone varieties. Under typical practices (*i.e.*, attempting timely harvest with standard manual methods), these operational harvest losses alone can range from approximately 6% to 15% of the potential yield, depending on the farming system and specific conditions (Usman *et al.*, 2022). Furthermore, in scenarios involving significant harvest delays or inexperienced handling, particularly with these highly susceptible landraces, total losses (including pre-harvest shattering and operational losses) can easily exceed 50%, highlighting the crop's inherent vulnerability (Gholamhoseini and Dolatabadian, 2024a).

These losses are aggravated by the crop's indeterminate growth habit, asynchronous capsule maturity, and dependence on labour-intensive harvesting practices. Mechanical harvesting remains rare in many sesame-producing countries, partly due to the fragility of traditional landraces and the lack of compatible agronomic traits, such as uniform maturity, non-shattering capsules, and suitable plant architecture (Langham and Wiemers, 2002).

Nevertheless, the successful mechanisation programs in several key countries offer promising insights. In countries such as Brazil, the USA, and China, the combination of shatter-resistant cultivars and adapted mechanisation technologies has transformed sesame into a commercially viable and scalable crop. For instance, Brazil exemplifies this transformation. The country's sesame cultivated area has surged dramatically in recent years, with production reaching approximately 361000 tons in the 2023/24 season, a significant increase driven by varietal improvement and widespread mechanization (FAOSTAT, accessed October 25, 2025). This rapid expansion has positioned Brazil among the world's top sesame exporters, demonstrating how integrating technology and breeding can unlock production potential on a global scale.

To address these challenges, this review synthesizes anatomical, physiological, and engineering insights to propose a sesame ideotype compatible with mechanised harvesting. While past reviews have often addressed either the genetics of shattering or harvesting technologies in isolation, this paper fills a critical gap by providing an integrated analysis that bridges these two fields. The integration of biological resistance and harvesting innovations holds the key to enhancing sesame productivity, economic viability, and global competitiveness, especially in regions where sesame remains an underutilised yet high-potential crop.

2. Capsule anatomy and mechanism of seed shattering in sesame

A comprehensive understanding of capsule anatomy is essential for designing both effective breeding strategies and mechanised harvesting technologies to reduce seed shattering. In sesame, the fruit is a capsule and its anatomical and histological structure plays a critical role in its natural tendency to shatter upon maturation (Bedigian, 2010). The sesame capsule is composed of three primary tissue layers: the epicarp (outer layer), the mesocarp (middle layer), and the endocarp (inner layer) (Day, 2000a). Each of these layers contributes differently to the biomechanics of seed retention or release.

The mesocarp consists of soft parenchymatous cells, while the endocarp is composed of heavily lignified sclerenchymatous cells, contributing rigidity and structural support (Day, 2000b). These endocarp cells form a hardened sheath around the locules but do not extend toward the placenta.

Table 1. Estimated sesame yield losses along the production-to-consumption chain.

Stage of loss in the production chain	Estimated quantity (kg ha^{-1})	Loss (%) (low-yield farm)	Loss (%) (hight-yield farm)	Primary causes	Source(s)
Pre-harvest losses	60–75	10.0–12.5	5.0–6.3	Pests, diseases, and weed competition	Gholamhoseini (2023)
Harvest losses	75–85	12.5–14.2	6.3–7.1	Asynchronous capsule ripening, high shattering tendency, manual harvest, and human error	Kelali *et al.* (2014)
Losses during postharvest drying	34–36	5.7–6.0	2.8–3.0	Over-drying immature seeds and pest infestation	Gebretsadik *et al.* (2019)
Losses during threshing	6–8	1.0–1.3	0.5–0.7	Manual threshing, lack of proper equipment	Kailashkumar (2019)
Losses due to unthreshed capsules	2–4	0.3–0.7	0.2–0.3	Improper drying leading to incomplete dehiscence	Usman *et al.* (2022)
Cleaning and sorting losses	2–4	0.3–0.7	0.2–0.3	Poor packaging, inadequate transportation	Usman *et al.* (2022)
Transportation losses (field to main storage)	2–4	0.3–0.7	0.2–0.3	Inadequate packaging	Neme *et al.* (2020)
Storage losses	2–4	0.3–0.7	0.2–0.3	Substandard storage conditions	Berhe *et al.* (2023)
Market packaging losses	6–8	1.0–1.3	0.5–0.7	Manual packaging, operator-related inefficiencies	Nyo *et al.* (2021)
Processing losses (*e.g.*, tahini production)	8–10	1.3–1.7	0.7–0.8	Lack of modern processing facilities	Nyo *et al.* (2021)
Unforeseen losses	2–4	0.3–0.7	0.2–0.3	Not specified	Usman *et al.* (2022)
Total estimated losses	**199–242**	**33.2–40.3**	**16.6–20.2**		

Average yield of low and high farm yield ≈ 600 and 1200 kg ha^{-1}, respectively.

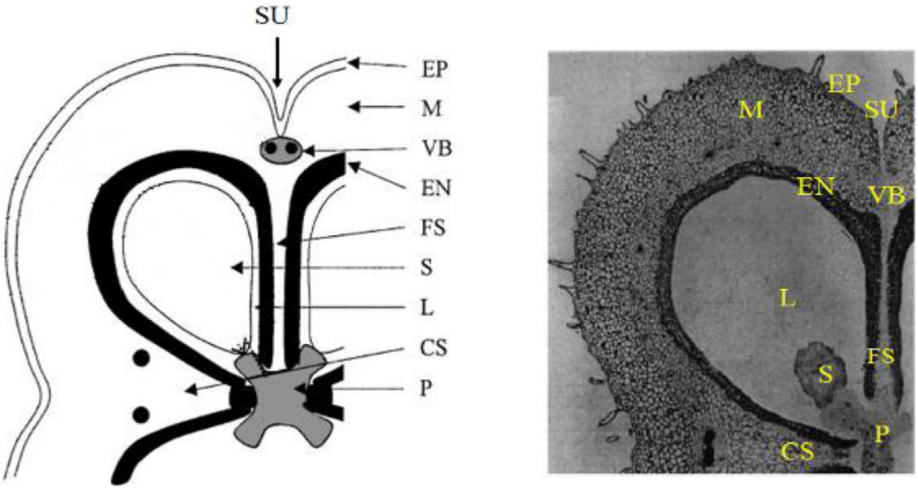

Fig. 1. Cross-section of a sesame capsule. Photo from Day (2000a). **SU**: Sutural gap, **CS**: Carpel wall, **EN**: Endocarp, **EP**: Epicarp, **FS**: False septum (pseudoseptum), **L**: Lumen, **M**: Mesocarp, **P**: Placenta, **S**: Seed, **VB**: Vascular bundle of the central axis.

Seeds are attached centrally within the capsule *via* placental connections (Fig. 1).

As the capsule matures and dries, longitudinal dehiscence occurs, starting from the apex and proceeding downward. This dehiscence is similar to that observed in other dry fruits, such as siliques in *Brassica* species. Two primary structural prerequisites have been identified for fruit dehiscence (Maity *et al.*, 2021):

Table 2. Summary of key morphological capsule traits for assessing shatter resistance.

Trait	Brief description	Scoring range	Optimal score for mechanized harvest
Capsule Dehiscence Score	Extent of longitudinal splitting from apex to base (Fig. 2a).	0 (Fully Open) 8 (Intact)	1 (Facilitates threshing)
Capsule Valve Opening Score	Degree of separation between valves at the capsule apex (Fig. 2b).	0 (Fully Open) 8 (Closed)	7 (Allows drying, prevents loss)
Membrane Coverage Score	Extent of membrane covering the seed cavity (Fig. 2c).	0 (None) 8 (Full)	7 (Retains seeds but is fragile enough for threshing)
Capsule Compactness Score	Tightness of the dried capsule, retaining seeds when inverted (Fig. 2d).	0 (Loose) 8 (Tight)	4–5 (Balances retention and release)
Seed–Placenta Adhesion Score	Strength of seed attachment to the central placenta (Fig. 2e).	0 (None) 8 (Strong)	7 (Withstands field vibration but yields to threshing)
Membrane–Placenta Contact Score	Proximity of the membrane to the placental axis.	0 (None) 8 (Complete)	5–8 (Retains seeds without hindering threshing)

1. Differential thickening or cell wall orientation among adjacent tissue layers, and
2. The presence of a predetermined zone of weakness, or abscission layer, along the capsule.

In sesame, the endocarp shrinks less than the mesocarp during dehydration. This disparity creates internal mechanical stress, promoting delamination between the layers and facilitating capsule opening. The greater the differential shrinkage, the higher the tendency for the capsule to split. Moreover, the orientation of sclerenchymatous fibres in the endocarp is not uniform along the capsule's longitudinal axis (Shtein *et al.*, 2016a), which contributes to both lateral dehiscence along the false septum and splitting from the capsule tip.

A critical feature in this process is the zone of weakness located in the false septum, a membranous structure separating the locules. This septum includes thin-walled parenchymatous cells that lie between vascular bundles and the epicarp. During early capsule development, partial enzymatic degradation of the parenchymatous cell walls occurs, primarily involving cellulases and pectinases, further weakening this region (Day, 2000c). Collectively, the asynchronous shrinkage of mesocarp and endocarp tissues, combined with the formation of the false septum as a structural weak point, creates the biomechanical basis for capsule dehiscence and seed shattering in sesame.

2.1. Capsule Traits Contributing to Seed Retention in Sesame

A standardised set of capsule traits is used to assess sesame shattering resistance, optimising both field seed retention and mechanised harvesting efficiency (Langham, 2011; Miao *et al.*, 2021). These morphological and anatomical indicators guide breeders in identifying genotypes suited to mechanical systems. The key traits, their scoring methods, and optimal ranges for mechanised harvesting are detailed in Table 2. These morphological indicators assess different aspects of both external and internal capsule integrity. Key traits include the extent of the capsule's longitudinal split (capsule dehiscence score) and the degree of opening at its apex (capsule valve opening score), which influences drying and initial seed loss. Internally, crucial traits are the completeness of the membrane covering the seed cavity (membrane coverage score), the overall tightness of the dried capsule (capsule compactness score), the strength of the seed's attachment to the central placenta (seed–placenta adhesion score), and the proximity of the membrane to the placental axis (membrane-placenta contact score) (Fig. 2).

Two qualitative traits further enhance retention: a non-curved capsule tip (Fig. 3) reduces rupture risk, and an upright capsule angle improves stability by minimising shake-induced dehiscence. Together with the quantified traits, these features strongly influence a genotype's suitability for mechanised harvest and resistance to preharvest shattering (Langham and Wiemers, 2002; Queiroga *et al.*, 2019). However, a major limitation in utilizing these internal traits (*e.g.*, membrane coverage) is the reliance on destructive and labor-intensive manual scoring. Unlike external features, assessing internal capsule architecture remains a bottleneck for high-throughput screening, highlighting the need for future research into non-destructive imaging techniques.

2.2. Quantification of seed shattering intensity

Reliable, standardised methods are crucial for evaluating seed retention and breeding shatter-resistant sesame. Two main systems are used: the TI/KE/TO Index (a numerical score for upright retention, inverted retention, and tip opening of capsules), developed by the US-based company Sesaco (Sesame Coordinators), and the Langham Method (Langham, 2013).

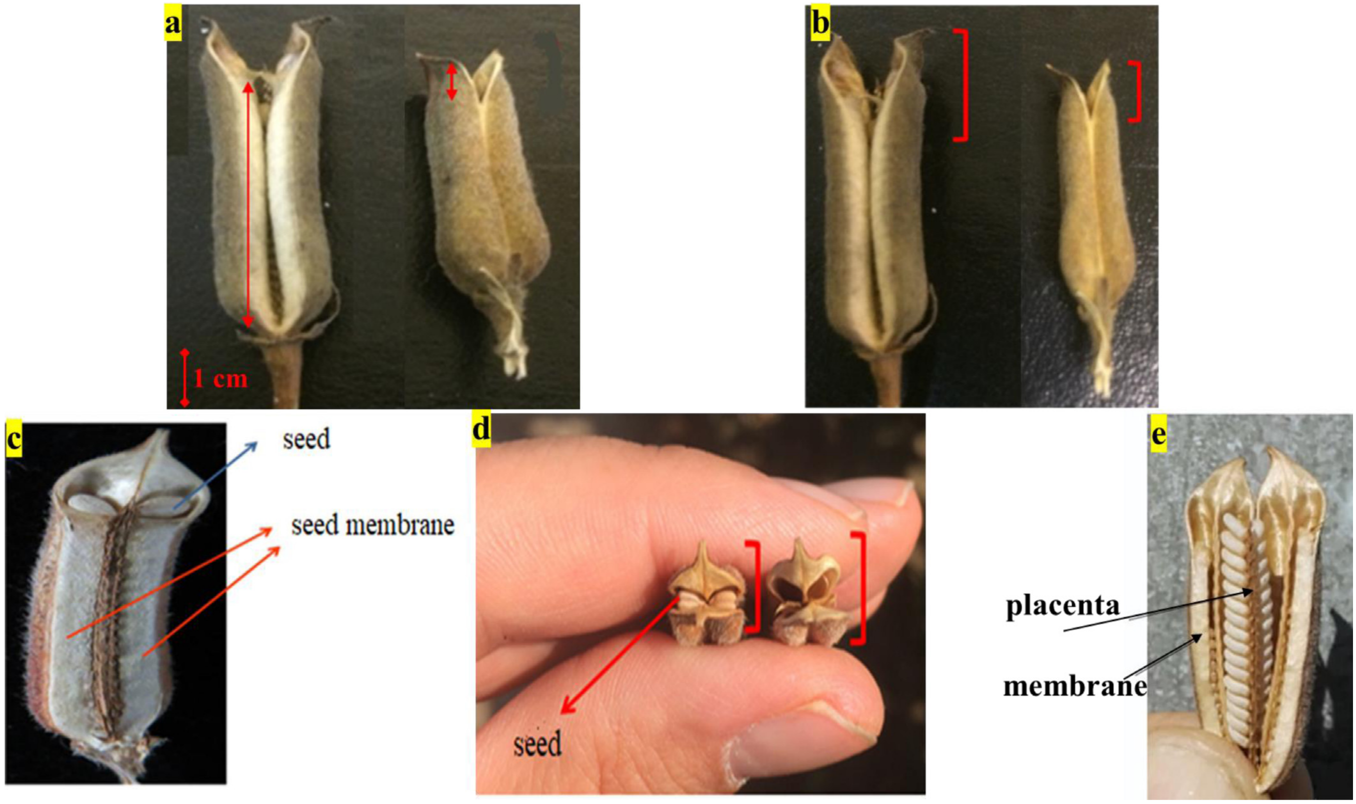

Fig. 2. Key morphological capsule traits influencing sesame seed retention and threshability. (a) Capsule dehiscence score: compares a generally shatter-resistant genotype (left) exhibiting a more complete suture split (score closer to 1), which facilitates seed release during threshing, *versus* a susceptible genotype (right) with a less extensive split. (b) Capsule valve opening score: illustrates differences in apical gap width (optimal score ~ 7 allows drying while retaining seeds). (c) Membrane coverage score: shows optimal coverage (score 7), which retains seeds pre-harvest but is fragile enough for threshing. (d) Capsule compactness (cross-section): highlights reduced apical gap in resistant (left) *vs.* susceptible (right) capsules (optimal score 4-5 balances retention and release). (e) Seed-placenta adhesion: illustrates seed attachment within the locules (optimal score ~ 7 withstands vibration but yields to threshing). Refer to Table 2 for detailed scoring. Scale bar in (a) = 1 cm

Fig. 3. Capsule A has tip curvature after drying, making it unsuitable for mechanical harvesting; Capsule B lacks curvature but lacks shattering resistance. Capsule C combines a non-curved tip with shattering-resistant traits, making it optimal. Photo by the authors.

Table 3. TI/KE/TO Index for evaluating seed shattering resistance of Iranian sesame cultivars.

Cultivar	TI	KE	TO	TI/KE/TO Index
Oltan	3	2	3	323
Darab 1	3	2	2	322
Dashtestan 2	3	1	2	312
Mohajer	7	7	6	776
Barekat	6	5	6	656

Data represent mean values obtained from replicated field trials. Measurements were taken approximately 14−21 days after physiological maturity, by which time the plants were fully dried under field conditions.

Table 4. Relationship between the TI/KE/TO Index and the harvesting method.

Harvesting method	Required TI/KE/TO index
Bundling: including cutting the plants (by machine or hand), bundling them, and threshing with a combine	TI > 4 KE > 3 TO > 4
Two-stage: including cutting the plants, leaving them to dry, and threshing with a combine	TI > 4 KE > 4 TO > 4
Direct: all harvesting operations performed by a combine	TI > 6 KE > 6 TO > 4

Source: Langham *et al.* (2010); Langham (2011).

2.2.1. The TI/KE/TO index: a numerical descriptor of shattering resistance

The TI/KE/TO Index is a three-digit score (0−8 for each digit) evaluating capsule seed retention under different conditions:

- TI (Upright Retention): This parameter assesses the seeds retained in capsules that have been allowed to dry naturally on the plant under field conditions. These vertically oriented capsules are then scored from 0 (empty) to 8 (full).
- KE (Inverted Retention): This score quantifies the capsule's ability to retain seeds when it is inverted and gently shaken, simulating the vibrational forces experienced prior to and during combine harvesting. It is considered the most critical indicator of suitability for mechanisation. Scores range from 0, where all seeds fall out easily, to 8, where seeds remain firmly attached. An optimal KE score for mechanised systems is typically in the mid-range (*e.g.*, 4 to 6), indicating a genotype that resists field shattering but allows for efficient seed release during threshing.
- TO (Tip Opening): This measures the degree of separation between the capsule valves at the apex after drying, scored on a scale from 1 (fully dehisced or wide open) to 8 (completely closed). While a low score indicates high shattering risk, a score of 8 is also undesirable as a fully closed tip can trap moisture and impede threshing. An optimal TO score is typically around 7, where the tip is only slightly open, allowing the capsule to dry effectively while still providing strong seed retention.

Fig. 4. Mature sesame seeds exhibiting the visual cues of physiological maturity, including colour change and a distinct dark hilum or longitudinal line (indicated by arrows), the stage targeted for sampling in Langham's shatter resistance assay. Photo by the authors.

To measure the TI/KE/TO index:

1 Select three mature, dried capsules from the mid-section of three plants.
2 Open each capsule longitudinally and score seed retention (TI scores).
3 Repeat with inverted capsules and record KE scores.
4 Assess the degree of tip opening and assign TO scores.
5 Average the scores across the nine capsules (three per plant × three plants) for each component.

Table 3 summarises the TI/KE/TO indices of several Iranian cultivars, while Table 4 provides threshold TI/KE/TO values recommended for various mechanical harvesting techniques.

To comprehensively assess seed retention stability, measurements should be conducted at four post-maturation stages: (1) immediately after physiological maturity and initial drying, (2) after two weeks of favorable weather, (3) following one week of unfavorable conditions (*e.g.*, rain or high humidity), and (4) one month post-drying under continued adverse weather. This protocol distinguishes genotypes with short-term shattering resistance from those with durable seed retention under field conditions (Gholamhoseini *et al.*, 2024a). Critically, while the TI/KE/TO index provides detailed morphological descriptors essential for breeding specific traits, it remains semi-quantitative and subject to scorer bias. Therefore, it is most effective when used as a preliminary selection tool, ideally complemented by direct physical retention assays for final validation.

2.2.2. Langham's method: a physical seed retention assay

In contrast to the semi-quantitative TI/KE/TO index, Langham's (2013) method provides a direct physical assay to quantify shattering resistance. The core principle of this

Table 5. Langham's index for evaluating seed shattering resistance in Iranian sesame cultivars.

Cultivar	Seed retention (%)	Capsule type
Oltan	34	Shattering
Darab 1	22	Highly shattering
Dashtestan 2	31	Shattering
Mohajer	89	Shattering-resistant
Barkat	78	Shattering-resistant

The presented values are the means from replicated field trials. Measurement timing: Capsules were sampled at physiological maturity, the stage at which ~ 75% of seeds in the mid-stem capsules had changed colour.

protocol is to harvest capsules precisely at physiological maturity—a stage typically reached around 40-50 days after flowering (depending on genotype and environment) (Langham, 2007) and visually indicated when approximately 75% of seeds within the mid-stem capsules change colour and exhibit a distinct dark hilum or longitudinal line (as shown in Fig. 4)-allow them to air-dry under controlled conditions, and then calculate the percentage of seeds retained after the capsules are simply inverted. This approach yields a clear, quantitative metric of seed retention. A major contribution of this method was its establishment of a practical classification system, where the >75% retention threshold became a widely accepted benchmark for identifying genotypes as resistant and suitable for mechanisation (Langham, 2000; Sadeghi *et al.*, 2022). While this assay is highly accurate for final selection in breeding programs, its manual nature may limit its application for high-throughput screening in early generations.

Capsules are classified into four shattering susceptibility categories based on seed retention: (1) Highly shattering (<25%; unsuitable for mechanical harvesting), (2) Shattering (2550%; still non-viable), (3) Moderately resistant (50-75%; marginal for commercial harvest), and (4) Resistant (>75%; optimal for mechanisation with minimal loss) (Langham, 2000, 2013). This framework uses the 75% threshold as the key benchmark for mechanisation potential (Sadeghi *et al.*, 2022). Table 5 shows Langham test results for Iranian cultivars.

2.3. Genetic and breeding approaches for enhancing seed retention in sesame

The increasing adoption of mechanised harvesting is fundamentally reshaping sesame production globally. This trend is exemplified by its standardisation in the United States (Langham and Wiemers, 2002) and the rapid expansion in Brazil (Queiroga *et al.*, 2019), where the integration of mechanisation-ready cultivars has been a key driver in boosting national production. Consequently, breeding for stable genetic resistance to seed shattering is a top priority. Agronomic adjustments offer short-term relief, but lasting progress relies on genetic improvement (Qureshi *et al.*, 2022; Gholamhoseini and Dolatabadian, 2024a). This section reviews strategies from traditional phenotypic selection to modern molecular approaches for developing machine-compatible sesame ideotypes.

2.3.1. Selection based on morphological indicators

Empirical observations across diverse environments have underscored the heritability of certain morphological traits associated with seed retention (Tinak Ekom *et al.*, 2025). Key features include capsule dehiscence angle, development of inner membranes across locule cavities, firmness of seed adhesion to the placenta, and the extent of capsule contraction during drying (Phumichai *et al.*, 2017). As discussed in previous sections, these traits can be systematically scored, creating a reliable foundation for phenotypic selection. Traditional breeding programs have effectively utilised such descriptors in recurrent selection cycles to enhance seed retention capacity gradually. A prime example is the breeding program in the United States, which systematically applied morphological scoring for capsule traits to develop the first commercially viable, shatter-resistant cultivars suitable for combine harvesting (Langham, 2013).

2.3.2. Incorporating resistance through landraces and exotic germplasm

Significant progress in developing shatter-resistant sesame varieties has indeed been achieved globally over recent decades, driven by targeted breeding efforts in various key regions. Screening of diverse germplasm has successfully identified valuable sources for shattering resistance. For instance, studies on Ethiopian landraces have identified accessions with moderate but stable seed retention (Gebremichael, 2017), which are valuable for improving environmental adaptability. A pivotal breakthrough in developing non-shattering sesame was the discovery of the recessive indehiscent (id) gene mutation in a Venezuelan landrace (Qureshi *et al.*, 2022). This single gene became the foundation for most of the shatter-resistant cultivars developed in the United States by breeders like Langham, leading to commercial varieties with near-complete seed retention. Similarly, breeding programs in Iran have successfully developed and released shatter-resistant varieties such as Mohajer and Barekat (Siahpoosh *et al.*, 2024), which combine this trait with high yield and desirable agronomic characteristics. These documented genetic resources have been instrumental in creating modern, mechanisation-ready sesame cultivars

2.3.3. Challenges in trait integration

A fundamental challenge in sesame breeding is to resolve the inherent conflict between two opposing selection goals: shatter resistance and threshability. The ideal capsule must be robust enough to prevent pre-harvest seed loss in the field, yet simultaneously fragile enough to release its seeds efficiently during mechanical threshing (Teklu *et al.*, 2022; Razaghi, 2024a). While tightly closed capsules effectively reduce pre-harvest losses, they may hinder seed release during threshing, thereby increasing harvest inefficiencies (Bedigian, 2004; Razaghi, 2024b). Breeding must therefore aim for a middle ground: ensuring capsule integrity during field drying while enabling clean seed release under mechanical impact. This balance is especially challenging due to the polygenic nature of shatter resistance, involving both structural and physiological factors (Uzun and Çağırgan, 2006; Sadeghi *et al.*, 2022).

Table 6. Key ideotype traits for mechanised sesame harvesting, their inherent trade-offs, and target parameters.

Ideotype trait	Demand for shatter resistance (field retention)	Demand for threshability (mechanical release)	Optimal balance and target parameters
Capsule Wall and Membrane Integrity	High structural integrity; resists environmental stress (wind, rain).	Brittle enough to fracture easily under combine impact.	A resilient membrane providing full coverage but engineered with fracture points responsive to 3–5 kN of mechanical impact (Shtein *et al.*, 2016b).
Seed-Placenta Adhesion	Strong adhesion to placental tissue to prevent vibration-induced loss.	Weak adhesion for effortless seed detachment during threshing.	Tunable adhesion that withstands low-frequency field vibrations ($\leq$2 Hz) but yields to high-frequency threshing forces ($\geq$25 Hz) (Langham, 2011 and 2013).
Apical Opening (Valve Score)	A completely closed tip (score 8) to maximise seed retention.	A wide opening (low score) for an easy seed exit path.	A minimal opening (score ~ 7) that permits drying while preventing spillage, optimising both stability and threshing (Langham, 2007).
Physiological Synchrony	Asynchronous maturity to hedge against total crop failure from a single stress event.	Uniform maturity and desiccation for a single, efficient harvest pass.	Uniform vascular senescence patterns ensuring synchronised moisture loss (8–12% gradient) along the entire fruiting zone (Day, 2000a).

Capsule architectural traits, such as locule wall thickness and partially fused capsule apices, have shown moderate to high heritability, offering potential for progress *via* conventional breeding (Yol, 2017). Nonetheless, combining traits like breakable yet strong membranes with moderate seed adhesion calls for advanced strategies, including marker-assisted selection (MAS) where possible.

2.3.4. Prospects for marker-assisted and genomic selection

To date, the molecular basis of seed shattering resistance in sesame remains only partially elucidated, a knowledge gap attributable to several key challenges. Primarily, shattering resistance is a complex quantitative trait, often controlled by multiple genes (QTLs) with small to moderate effects, making its genetic architecture difficult to dissect (Wang *et al.*, 2023). Furthermore, sesame has historically received less research focus compared to major staple crops, resulting in a slower development of comprehensive genomic tools and resources needed for functional gene studies (Gholamhoseini and Dolatabadian, 2024a). However, the landscape of sesame genomics has been transformed by recent technological advances, particularly the advent of high-throughput Next-Generation Sequencing (NGS) and the subsequent development of a high-quality reference genome (Weldemichael and Gebremedhn, 2023). These tools have opened promising avenues for identifying genetic markers associated with key structural traits (Wang *et al.*, 2022; Dossa *et al.*, 2017a). Preliminary QTL mapping and transcriptome studies have highlighted genes involved in cell wall lignification (gene SIN_1005755) (Xu *et al.*, 2021), pectin methylesterase activity (Wang *et al.*, 2018 and 2023), and cellulose biosynthesis (Dossa *et al.*, 2018), each contributing to the mechanical resilience of capsule tissues. More specifically, several resistance-related QTLs have been mapped on chromosomes 3, 5, and 7, providing key targets for marker-assisted breeding (Wang *et al.*, 2023). A particularly significant finding is the identification of *SiHEC3*, a candidate gene on chromosome 3, where a specific deletion in its promoter region has been strongly correlated with delayed capsule opening and enhanced seed retention (Ju *et al.*, 2024)

The validation of these candidate genes and QTLs is a critical next step. Once confirmed, these markers can be deployed in marker-assisted breeding programs to facilitate the introgression of resistance alleles into elite cultivars, thereby accelerating genetic gain without compromising other vital agronomic traits such as yield, oil content, or drought tolerance (Ataei *et al.*, 2017). Prioritizing the development of robust, cost-effective markers for these specific QTLs and particularly for the functional polymorphism in the *SiHEC3* gene, therefore, represents the most immediate and high-impact strategy for implementing MAS to improve shatter resistance in elite sesame backgrounds (Li *et al.*, 2023). Despite these promising identifications, a significant gap remains in the functional validation of these markers across diverse genetic backgrounds. Most currently identified QTLs are population-specific, which limits their broad application in global breeding programs. Consequently, the development of diagnostic, gene-based markers that are stable across different environments represents the next critical priority for molecular research.

2.3.5. Toward ideotypes for mechanised harvest

The primary goal in modern sesame breeding is to develop capsule ideotypes that combine two opposing traits: maximal seed retention during pre-harvest desiccation and rapid,

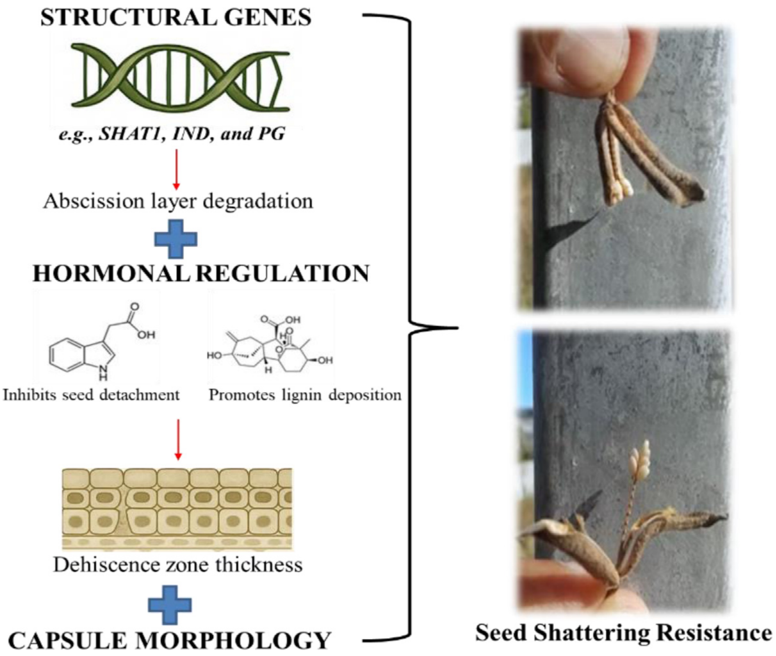

Fig. 5. Genetic and hormonal regulation of seed shattering resistance in sesame. The schematic illustrates key molecular and morphological determinants of shattering resistance, including: Structural gene networks (*e.g.*, SHATTERING1 [SHAT1], INDEHISCENT [IND], and Polygalacturonase [PG] genes) controlling cell wall degradation at the abscission layer; hormonal regulation by auxin (inhibiting abscission) and gibberellin (promoting lignin deposition) and capsule morphology traits, such as dehiscence zone thickness and vascular bundle orientation, that mechanically constrain capsule opening.

complete seed release during mechanical threshing (Langham and Wiemers, 2002; Uzun and Cagirgan, 2006; Gholamhoseini *et al.*, 2024b). Achieving this goal requires optimising several key traits, each involving a fundamental trade-off. The ideal balance integrates specific biomechanical and physiological targets, as summarised in Table 6.

This goal demands coordinated research integrating next-generation phenotyping (*e.g.*, micro-CT valve analysis), biomechanical modelling of harvester-pod interactions, and molecular breeding targeting loci for lignin deposition (CCoAOMT) and abscission layer development (polygalacturonase regulators) (Fuller and Allaby, 2009; Dong and Wang, 2015; Li and Olsen, 2016), validated through multi-environment field trials to match genotype, management, and machinery.

2.3.6. Molecular and genetic regulation of seed shattering resistance in sesame

Advances in genomics are rapidly uncovering the complex regulatory networks that govern shattering resistance. Beyond the specific QTLs and candidate genes mentioned previously, transcriptome-wide studies are revealing broader patterns. These include the differential expression of genes involved in lignin deposition, pectin modification, and cellulose biosynthesis, which collectively reinforce capsule structure (Wang and Brutnell, 2010; Maity *et al.*, 2021). Furthermore, key hormonal pathways–particularly those involving auxin and ethylene–show distinct expression profiles in resistant *versus* shattering-prone genotypes, indicating their role in regulating abscission zone development (Liu *et al.*, 2024; Wu *et al.*, 2023). Insights from model species like *Arabidopsis*, rice, and soybean continue to be invaluable for identifying orthologous genes in sesame, accelerating functional validation studies (Wang *et al.*, 2022). As illustrated in Figure 5, a systems-level understanding of these integrated networks is now forming the basis for genomics-assisted breeding of mechanisation-ready sesame.

3. Mechanised harvesting of sesame

3.1. Mechanised harvesting methods

The transition from traditional manual harvesting to mechanization represents a pivotal step for enhancing sesame production efficiency, but involves navigating significant trade-offs. Manual harvesting, while adaptable to shattering-prone varieties and requiring minimal capital investment, suffers from high labor costs, significant harvest and post-harvest losses (often 15–50% as detailed in Tab. 1), and limitations in scalability. Mechanized harvesting, conversely, offers the potential for drastically reduced labor requirements, faster operations, and lower operational losses if implemented correctly, but faces challenges related to high initial investment, the need for shatter-resistant cultivars with suitable architecture, and precise machine calibration. Therefore, the core strategy to minimize overall losses and maximize economic benefits hinges on successfully bridging the gap between sesame biology and engineering-developing suitable ideotypes (Sect. 2.3.5) and optimizing harvesting technologies (Sect. 4)–which forms the central theme of this review.

Technological progress for sesame mechanization has involved both adapting existing combine harvesters (primarily through header and threshing/cleaning adjustments detailed later) and, to a lesser extent, developing specialized or smaller-scale

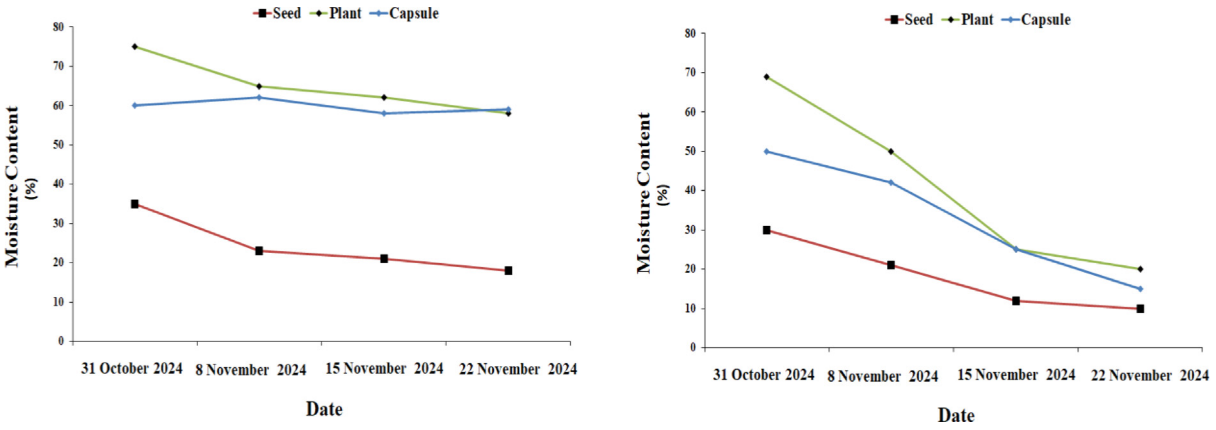

Fig. 6. Natural moisture variation trends in standing sesame plants (for direct harvest method, left image) *versus* two-stage harvested plants (right image) for whole plants, capsules, and seeds in Golestan Province, Iran. Unpublished data from the authors.

harvesting equipment tailored to the crop's specific challenges (Bandhiya *et al.*, 2023, Pari *et al.*, 2020). The mechanised harvesting of sesame is primarily done using two main approaches: (1) two-stage (indirect) harvesting, which involves cutting the plants and allowing them to dry in the field before threshing, and (2) direct harvesting with a combine harvester (Bazyar *et al.*, 2019; Razaghi, 2024a).

In humid or cool regions such as northern Iran (Golestan, Mazandaran), where sesame is sown from late May to mid-June (Gholamhoseini, 2020), ripening often coincides with autumn rains and high humidity, delaying drying and making direct combining impractical due to elevated grain moisture and mechanical risks (Usman *et al.*, 2022). Under such conditions, two-stage harvesting is preferred: plants are cut and windrowed to accelerate drying *via* improved air circulation and solar exposure (Fig. 6). This lowers seed moisture to safe levels for threshing and storage, and shortens the interval before the next crop, boosting productivity and resource efficiency. However, it requires extra labour and machinery for cutting and threshing, increasing costs compared with direct harvesting under favourable climates (Razaghi, 2024b).

3.2. Optimal harvest timing: a key factor in minimising losses

Accurate harvest timing is essential to balance seed maturity, minimise shattering, and ensure compatibility with mechanised operations (Neme *et al.*, 2020). Harvesting too early yields immature seeds from apical capsules, reducing yield and quality (Saboury *et al.*, 2021), while delays increase shattering risk and seed moisture, especially under poor weather (Gholamhoseini *et al.*, 2023a).

The optimal window depends on the harvest method (Langham *et al.*, 2010). In two-stage harvesting, plants are cut when ∼ 70−80% of mid-stem capsule seeds are mature-indicated by colour change and a dark hilum–while lower stems yellow and upper stems remain greenish-yellow, allowing remaining seeds to ripen during field drying (Doko and Enwere, 2014). This minimises losses and shortens post-harvest drying. For direct combining, seed moisture should be ∼ 6% for proper threshing (Langham *et al.*, 2010; Benaseer *et al.*, 2018). Field cues include brittle capsules, breakable stems, dust clouds during harvest, and uniform grain flow. Given the potential for moisture variability across a field, ensuring optimal harvest timing may require either staggered harvesting or diligent moisture monitoring. The latter is practically achieved using portable digital moisture meters to confirm that seed moisture has reached the target level of approximately 6% before combining begins (Gholamhoseini, 2023).

4. Direct (one-stage) harvesting of sesame

Direct harvesting (one-stage or combine harvesting) integrates cutting, threshing, and seed collection in a single pass using a combine harvester (Rithiga *et al.*, 2024). Success depends on synchronising plant maturity with optimal field drying (Price *et al.*, 1996). Cultivar traits-particularly capsule shattering resistance and plant architecture–also influence suitability for direct combining (Dossa *et al.*, 2017). The following sections address technical, agronomic, and equipment considerations for one-stage harvesting.

4.1. Complementary plant traits for direct (single-pass) harvest of sesame

In addition to capsule-related traits that constitute the necessary conditions for successful mechanised sesame harvesting, a set of sufficient complementary plant traits can further enhance the efficiency and quality of direct (single-pass) harvest operations. These traits influence key aspects such as seed maturity synchronisation, plant architecture compatibility with combine machinery, and post-harvest seed quality. For instance, uniform maturity is essential for minimising losses from asynchronous ripening, while physical traits must be compatible with the combine's header. Critical examples include an optimal plant height (120−150 cm) for smooth feeding and a sufficient height to the first capsule (15−30 cm) to allow for a clean cut. These and other key complementary traits are summarised in Table 7.

Table 7. Complementary morphological and physiological traits contributing to efficient direct sesame harvest.

Trait	Desired feature	Functional role in mechanized harvest	References
Cessation of flowering	Use of determinate genotypes or irrigation termination to synchronize maturity	Ensures uniform seed maturity, reduces shattering losses	Dutta *et al.* (2022); Gholamhosseini *et al.* (2022a)
Leaf shedding	Complete defoliation at harvest	Reduces foreign material, minimizes pest contamination	Razaghi (2024b)
Capsule retention	Strong attachment; narrow capsule-stem angle	Prevents capsule loss due to wind or agitation	Queiroga *et al.* (2019)
Upper capsule maturity	Early maturation of upper capsules	Prevents loss of immature seeds during threshing	Langham and Wiemers (2002)
Plant height	≤150 cm (ideally 120–130 cm) (Fig. 7)	Ensures proper feeding into combine header	Langham (2014); Miao *et al.* (2021)
Height to first capsule	15–30 cm from soil surface by adjusting planting density and arrangement (Fig. 7)	Allows low cutting height without crop loss or machine damage	Habibzadeh and Gholamhosseini (2022)
Branching pattern	Moderate branching (3–4 side branches)	Aids feeding into combine; prevents excessive entanglement	Beech and Imrie (2001)
Lodging resistance	Strong stems, moderate height, proper spacing by adjusting planting density and arrangement	Maintains upright posture for clean cutting and threshing	Gholamhosseini *et al.* (2022b)

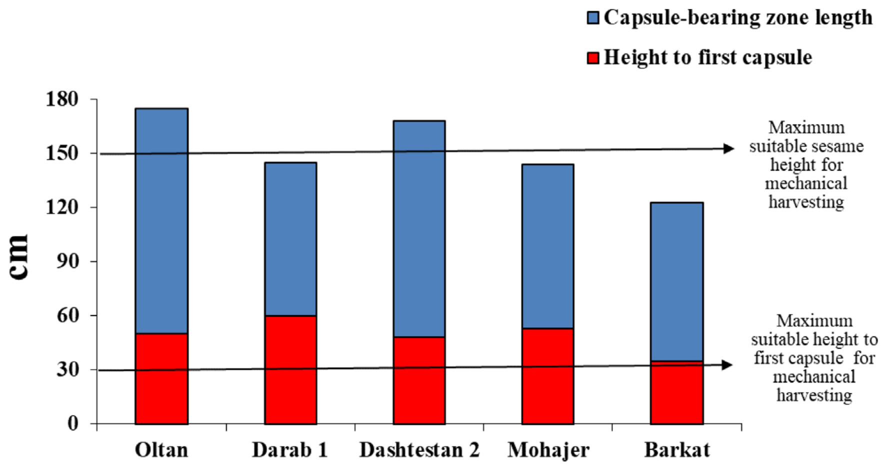

Fig. 7. Height to first capsule from ground level, capsule-bearing zone length, and total plant height in Iranian sesame cultivars. Data from Siahpoosh *et al.* (2024) and Karimi *et al.* (2019).

4.2. Optimising combine-harvester dynamics for sesame's unique biological traits

While most modern combine harvesters can be adapted for sesame, achieving an efficient and high-quality harvest requires a fundamental shift away from standard cereal settings towards a highly specialized calibration. The critical importance of precise calibration is vividly illustrated in Figure 8, which shows the stark difference in the quality of the final product between an optimised and a sub-optimally configured harvester.

The optimisation process begins well before the harvest itself, with a crucial preparatory phase 30-40 days prior, involving thorough cleaning of the harvester with compressed air to eliminate residual grains and weed seeds, and sealing any potential leakage points. This pre-harvest diligence alone can prevent cross-contamination and reduce subsequent processing costs by up to 30% (Razaghi, 2024a and b).

The initial interaction with the crop at the combine's header is a critical stage where significant losses can occur. To minimise these losses, which can range from 18–22% with improper settings (Sadeghi *et al.*, 2022), the reel speed must be precisely synchronised to be approximately 25% faster than the ground speed (a reel index of 1.0-1.5), making contact with only the top 15 cm of the plant (Elebaid *et al.*, 2016). This gentle handling prevents the violent agitation that causes premature shattering in susceptible genotypes.

Fig. 8. Comparison of harvested sesame yield using a combine harvester with optimised settings (right) *versus* suboptimal configurations (left). Photo by the authors.

The core of the operation–the threshing unit–demands the most significant adjustments. Sesame's delicate, high-oil seeds are highly susceptible to mechanical damage. Consequently, a much less aggressive threshing action is required compared to hardier grains. This is achieved by using slightly worn serrated cylinders and, most importantly, by reducing the cylinder speed to a low range of 350−500 rpm while widening the concave clearance to 25−30 mm at the front and 12−17 mm at the rear (Ishpekov *et al.*, 2014; Eindhuja *et al.*, 2022). These settings are designed to ensure that seed damage remains below a 2% threshold (Narayanan *et al.*, 2024). An improper balance here can lead to either excessive seed breakage or a high percentage of unthreshed capsules exiting the machine, necessitating a methodical, single-variable adjustment approach for troubleshooting (Kailashkumar, 2021; Razaghi, 2024a). This engineering adjustment is directly dictated by the biological traits described in Section 2.1; specifically, genotypes with high membrane coverage and seed-placenta adhesion scores (providing structural resistance) require a careful increase in cylinder impact force to ensure release, whereas varieties with lower adhesion scores must be harvested at minimum cylinder speeds to prevent seed micro-damage. This necessity to fine-tune machine parameters based on specific capsule histology underscores the critical interdependence of biology and engineering in sesame mechanization.

Finally, the separation and cleaning process must be adapted for sesame's small seed size (Bandhiya *et al.*, 2023). This involves using fine-mesh sieves (*e.g.*, an upper sieve of 4−12 mm and a lower one of 2−6 mm) and carefully calibrating the fan speed (initially 650−750 rpm) to create an airflow sufficient to remove chaff without blowing the lightweight seeds out of the combine–a common source of significant yield loss (Langham *et al.*, 2010). Even the final stages of grain handling, such as auger and elevator operation, must be managed to avoid damage from sharp edges or excessive initial torque during unloading. The operational efficiency is further modulated by the combine's forward speed, which must be calibrated based on field size and crop density, ranging from as low as 1.5 km/h in dense stands on small farms (Noorani *et al.*, 2023) to over 11 km/h in sparse stands on large, level fields (Langham *et al.*, 2010). Figure 9 provides a schematic overview summarizing these critical interactions between key capsule traits and the necessary combine harvester parameter adjustments. A summary of the specific recommended settings for these adjustments is provided in Table 8.

5. Evaluation of sesame yield losses in direct combine harvesting

While the Sesaco and Langham methods are valuable for quantifying a genotype's intrinsic shatter resistance potential under controlled conditions, they can not replicate the complex and dynamic forces of a real-world harvest. These laboratory-based assays do not account for the cumulative effects of machine-crop interactions–such as reel impact, cutter bar vibrations, and threshing forces-or the influence of variable environmental conditions.

Therefore, field evaluation of seed losses during mechanised harvesting remains essential to assess a genotype's true performance within a complete agricultural system. Actual machine-induced seed loss during harvesting differs significantly from pre-harvest natural shattering (Loss type 1, Fig. 10), which can exceed 50%insusceptiblevarieties left to dry fully before direct combining (Gholamhoseini and Dolatabadian, 2024a). Focusing on losses during the operation itself, machine related losses are often reported between 5–15% for direct combining (Naydenov *et al.*, 2020; Razaghi, 2024a), where as losses from mechanical handling in two-stage harvesting typically range from 3–10% (Sadeghi *et al.*, 2022; Razaghi, 2024b). During direct combining, these operational losses primarily occur at three key machine points, as illustrated in Figure 10:

- Cutting unit losses (Loss type 2): Seed or branch loss caused by cutting blade vibrations, wheel and reel impacts, and partial throwing of branches outside the header.

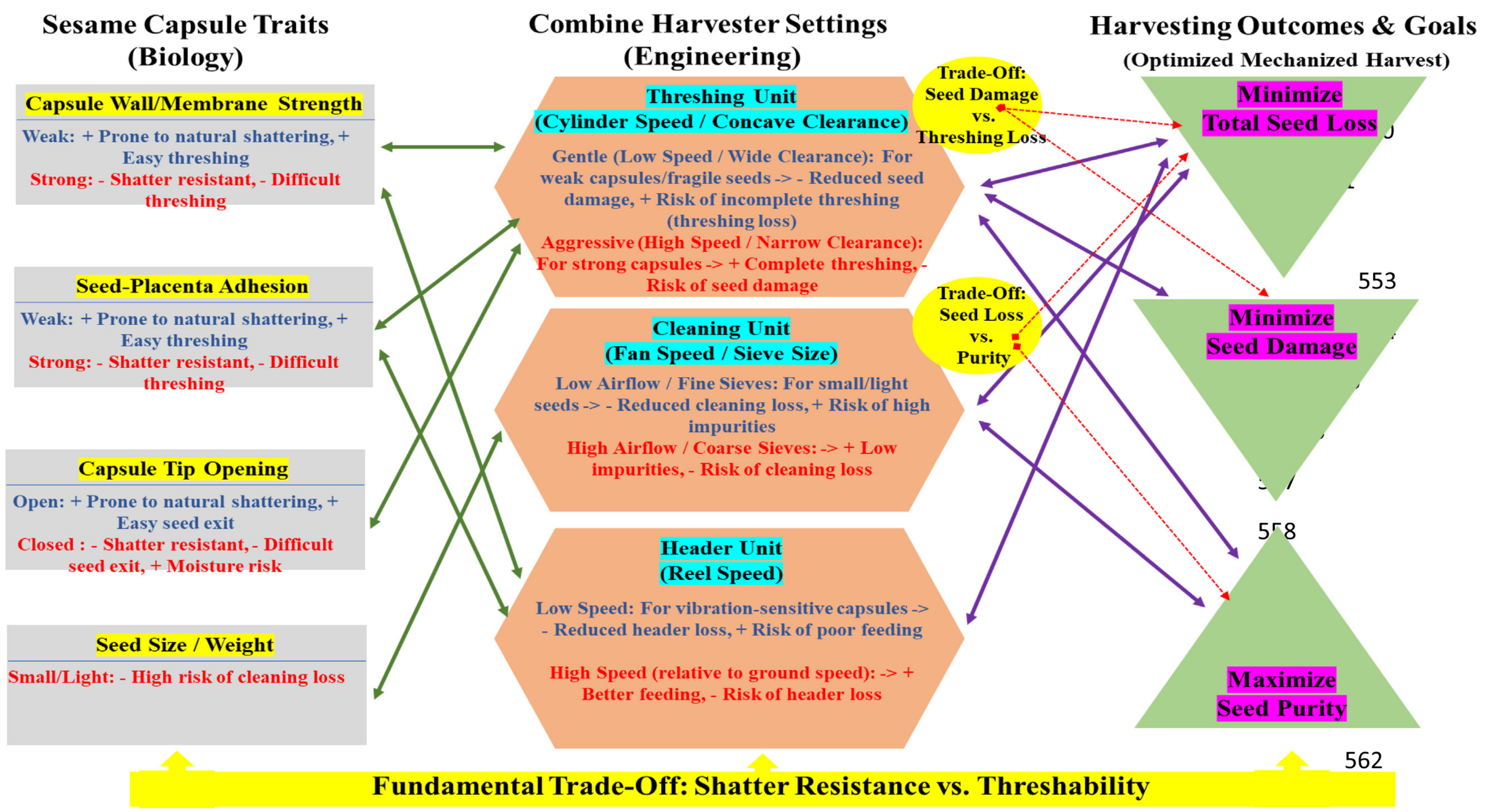

Fig. 9. Schematic flow diagram illustrating the critical interactions between sesame capsule traits (biology) and combine harvester settings (engineering) for optimized mechanized harvesting. The diagram highlights how specific capsule characteristics necessitate adjustments in threshing, cleaning, and header units to achieve the desired outcomes (minimized loss, minimized damage, maximized purity), while emphasizing the inherent trade-offs involved in balancing shatter resistance with threshability.

Table 8. Key combine harvester adjustments for direct sesame harvesting.

Component	Adjustment detail	Recommended range/note
Pre-Harvest Cleaning	Remove previous residues, seal leaks, and clean with air	30–40 days before harvest
Cutting Platform	Auger-sickle clearance, reel speed index, and cutting height	Clearance: 600–620 mm; Reel index: 1.0–1.5
Reel & Feeder	Reel contacts the last 15 cm of the plant, synchronised with the feeder speed.	Reel speed ~ 25%> forward speed
Threshing Unit	Cylinder speed, concave clearance, cylinder wear level	Speed: 350–500 rpm; Clearance: 25–30 mm (front), 12−17 mm (rear)
Straw Separator & Cleaning	Fan speed, sieve size and sequence, tail sieve, and airflow control	Fan: 650–750 rpm; Upper sieve: 4–12 mm; Lower: 2−6 mm
Grain Handling	Sharp edge inspection, unloading sequence	Start unloading at low speed, then increase
Forward Speed	Adjust according to farm size and crop density	Big farm (more than 5 ha): Dense: 1.5–2.0 km/h; Sparse: 2.0−2.5 km/h Small farm (less than 5 ha): Dense: 4.8–6.4 km/h; Sparse: 6.4–11.3 km/h

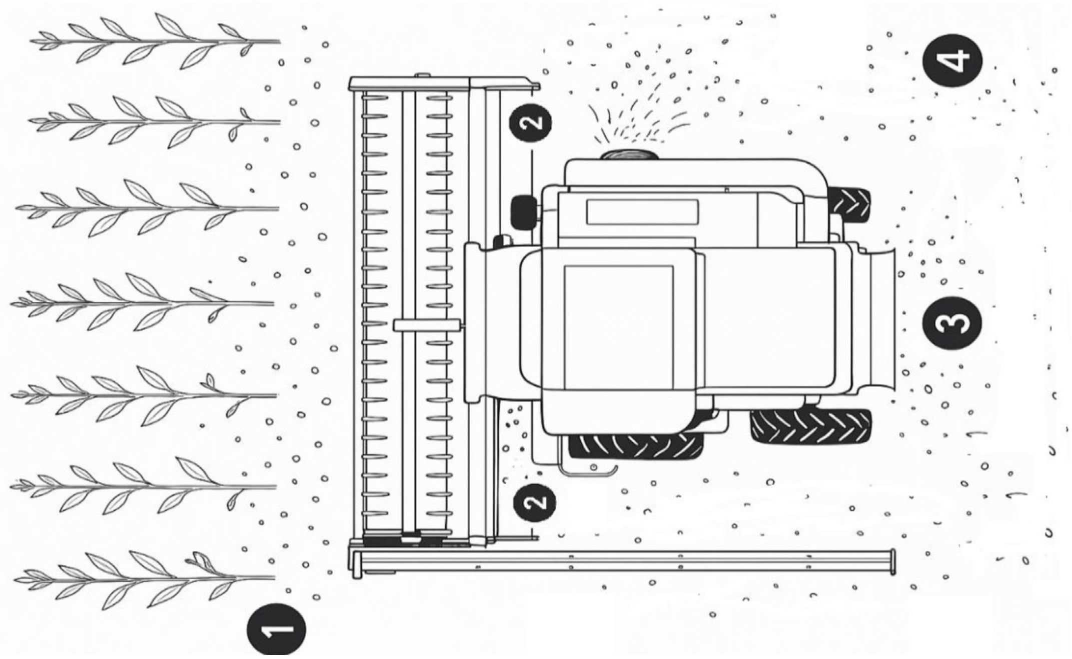

Fig. 10. Schematic illustration of seed shattering assessment points during mechanised sesame harvesting. (1) Natural shattering site, (2) Header unit shattering site, (3 & 4) Threshing and cleaning unit shattering sites. Source: Authors.

- Unthreshed capsules in combine discharge (Loss type 3): Due to ineffective threshing and separation, whole capsules may exit the combine with the straw.
- Losses from the cleaning unit (Loss type 4): Seeds lost through cleaning due to improper settings of the cleaning system and fan airflow.

Therefore, a thorough field assessment must quantify these different loss components, alongside the efficiency of seed release (threshability) and any resulting seed damage. Reliable evaluation of these factors requires plots $\geq$0.5 ha to ensure stable combine operation and avoid confounding edge effects, and a seed moisture of ~ 6%, as higher levels impede threshing and increase seed damage (Langham, 2014; Razaghi, 2024a)

5.1. Determination of actual seed yield

Accurate estimation of the actual seed yield (kg ha^{-1}) is essential for assessing losses from natural shattering and mechanised harvesting. To account for spatial variability, sample at least four representative points per hectare (Gholamhoseini, 2022b). At each point, harvest sesame plants from a 1 m^2 area using a standard frame and garden shears to avoid disturbance losses (Ishpekov and Stamatov, 2015). Separate capsules on a clean surface, extract seeds manually or with a small

Table 9. Summary of key parameters and methods for evaluating seed loss and post-harvest quality in mechanised sesame harvesting.

Parameter	Definition/measurement method	Sampling tools/conditions	Result expression
Actual Seed Yield (Y_{actual})	Total seed yield per unit area before machine harvest losses, determined by manual harvesting.	Harvest plants from ≥4 quadrats (*e.g.*, 1 m^2) per hectare.	kg ha^{-1}
Natural Shattering Loss ($S_{natural}$)	Seeds lost from capsules due to environmental factors before the combine passes.	Collect all fallen seeds/capsules from quadrats placed on the ground before harvest.	kg ha^{-1}
Header Loss (S_{header})	Seeds lost due to the impact and vibration of the combine's header (reel, cutter bar).	Place collection trays on the ground to capture losses only from the header pass.	kg ha^{-1}
Threshing Loss ($S_{threshing}$)	Seeds remaining in unthreshed or partially threshed capsules exiting the combine.	Collect and manually thresh capsules from the straw walker discharge.	kg ha^{-1}
Cleaning Unit Loss ($S_{cleaning}$)	Viable seeds lost from the rear of the combine with the chaff due to airflow/ sieve issues.	Collect and sieve the material discharged from the cleaning shoe.	kg ha^{-1}
Seed Loss	The percentage of each loss type relative to the actual seed yield.	Calculated as:% Loss =(S_x/Y_{actual}) × 100, where Sx is an individual loss component.	%
Seed Release Efficiency	The proportion of seeds successfully threshed from capsules by the combine.	Compare seed count in handthreshed reference capsules *vs*. machine-harvested capsules.	%
Seed Damage	The proportion of mechanically broken or cracked seeds in the final harvested sample.	Visually inspect and weigh damaged *vs*. intact seeds from a representative tank sample (*e.g.*, 100 g).	%

thresher and weigh them (in grams). The actual seed yield per hectare is then calculated using the following formula:

$$\text{Actual Seed Yield}(\text{kgha}^{-1}) = [\text{Average seed mass from sample}(\text{g})/\text{Sample area}(\text{m}^2)] \times 10$$

5.2. Estimation of natural shattering losses in the field

Natural seed shattering is the spontaneous seed detachment before mechanical harvesting, causing pre-harvest yield loss (Gan *et al.*, 2008). In sesame, losses depend on genotype-specific capsule traits and environmental stressors such as wind, rain, and humidity fluctuations (Dash *et al.*, 2018). Quantification uses sampling frames placed gently at random field sites (excluding borders) to avoid disturbance. All visible seeds and capsules on the soil surface are collected; if incomplete, losses are estimated from capsule counts and thousand-seed weight (Gan *et al.*, 2016).

5.3. Estimation of cutting unit losses and calculation of harvest loss percentage

This loss category includes seeds dislodged by the combine header during cutting. These losses are particularly high in genotypes sensitive to the mechanical shocks from the reel and the vibrations from the cutter bar (Domeika *et al.*, 2008). For example, traditional Iranian cultivars such as Darab 1 and Dashtestan 2, which are documented as highly shattering in Tables 2 and 4, are prime examples of genotypes susceptible to such header losses. Assessment uses 0.5 m^2 seed loss frames (10 cm height, 2 cm wall, fine mesh bottom) placed at four sampling sites–two per site–behind the header at its central and lateral thirds. Frames are positioned to exclude combine discharge and external seeds, with any plant parts extending inward trimmed (Eckert *et al.*, 2011). After harvest, free seeds and seeds from manually threshed capsules within frames are weighed. In addition, to express measured seed losses as percentages of yield, the following formula is used:

$$\text{Loss percentage} = (\text{Loss amount} \times 100)/\text{Final yield}$$

5.4. Assessment of seed release efficiency from capsules

Assessing seed release efficiency, a direct measure of a genotype's threshability, is critical as it impacts both yield and quality. Inefficient release leads to direct yield loss through unthreshed capsules and can indirectly degrade seed quality, as operators may resort to more aggressive, damaging combine settings to compensate. To assess seed release efficiency during mechanised harvesting, a comparative capsule-counting method is used (Razaghi, 2024a and b):

- Mechanically harvested capsules – Randomly collect 100 partially or unthreshed capsules from the combine's output (often from frames used in threshing loss assessment) and count remaining seeds.
- Reference capsules – Randomly select 20 plants from the field interior (≥50−100 m from edges); pick five mature capsules per plant from various positions (excluding immature apical

Table 10. Internationally recognised quality standards for graded sesame seed lots based on key physical and chemical attributes.

Attribute	Premium quality	Good quality	Standard quality
Moisture content (%)	<5.0	<6.0	<7.0
Immature seeds (%)	<0.5	<2.0	<3.0
Foreign matter (%)	<0.1	<2.0	<2.5
Weed seeds (no per kg)	0	<15	<38
Damaged seeds (%)	<0.4	<1.5	<3.5
Oil content (%)	≥52	≥50	≥47

Source: CBI Market Information (2025); Chinese Standard (2025); AGMARK Standards (2025).
Any increase in seed quality above the standard level is associated with a proportional increase in market value.

capsules) and count total seeds from these 100 capsules. The seed release percentage is calculated as follows:

$$\text{Seed release}(\%) = [(\text{Seeds in reference capsules} - \text{Seeds remaining in harvested capsules}) \div \text{Seeds in reference capsules}] \times 100$$

5.5. Evaluation of seed damage during mechanised harvesting

Seed damage is a key quality metric in mechanised sesame harvesting (Narayanan *et al.*, 2025). To assess it, harvesting continues until the grain tank is nearly full. Samples are taken from four positions and depths within the tank, combined, and mixed into a 60 g composite (Wang *et al.*, 2021). Seeds are classified as: (1) intact, (2) damaged/broken, and (3) immature seeds, weed seeds, and foreign material. For damage estimation, only the first two categories are used. After separating and weighing intact and broken seeds, the damage percentage is calculated as:

$$\text{Seed damage}(\%) = [(\text{Weight of broken seeds})/(\text{Weight of intact} + \text{broken seeds})] \times 100$$

A summary of the key procedures and measurements described in Section 5 is presented in Table 9.

5.6. Standards for seed shattering resistance in mechanised sesame harvesting

According to the framework proposed by Langham (2014) and Gholamhoseini (2022b), a sesame genotype can be considered resistant to shattering and suitable for direct combine harvesting if it meets the following four criteria:

1. At least 85% of seeds must remain within the capsules until the harvest date, when seed moisture content has declined to 6% or less (*i.e.*, natural seed shattering <15%).
2. Maximum 7% seed loss should occur during direct combine harvesting (header and cleaning units combined).
3. Maximum 5% of seeds may remain unreleased in the capsules after harvest.
4. Seed damage due to mechanised harvest must not exceed 3%.

These quantitative thresholds serve as an operational benchmark for evaluating breeding lines and assessing the field readiness of mechanised sesame harvest systems.

6. Quality control of mechanically harvested sesame seed

Maintaining sesame seed quality after mechanical harvest is essential for domestic and export markets (Angamuthu *et al.*, 2025). Quality standards should be followed throughout production, harvest, and post-harvest processes (Neme *et al.*, 2020). While no official national sesame standards exist in Iran or many major producing countries, internationally recognised benchmarks define key export parameters (Tab. 10).

Untimely harvest, particularly at high seed moisture, reduces quality (Gholamhoseini, 2023). Field-wide moisture assessment and avoiding high-humidity hours (early morning/late evening) are crucial. Full physiological maturity is required, as late planting or cold during seed filling increases immature seeds that must be removed post-harvest (Gholamhoseini and Dolatabadian, 2024a). Foreign materials–broken seeds, weed seeds, soil, stones, debris, or insects—lower market value and raise moisture and spoilage risk (Peariso, 2008). Weed seeds are a particularly problematic foreign material as they also spread infestations (Duary, 2014); control measures range from in-field management and pre-harvest combine cleaning to segregating weedy areas during harvest and utilizing advanced cleaning systems (*e.g.*, optical sorters) post-harvest (Gholamhosseini and Mansouri, 2024). Proper adjustment of airflow, sieves, and fans minimises these contaminants overall.

Seed damage mainly stems from incorrect combine settings. While optimally configured systems aim for damage rates below 3.5%, improper settings can easily cause mechanical damage exceeding 10%, significantly reducing market value (Razaghi, 2024a). Causes include excessive threshing speed, narrow concave clearance, overfilled grain tanks, and harvesting above 6% moisture (Razaghi, 2024b). Sharp edges on threshing or conveying parts can also harm oil-rich seeds. Damaged and moist seeds deteriorate quickly, making correct combine adjustment vital for quality assurance (Afzal *et al.*, 2019). Achieving high-quality mechanically harvested sesame therefore requires an integrated approach, managing factors from field conditions (maturity, weeds, moisture) through to precise combine calibration (settings, speed) and careful post-harvest handling. Adherence to internationally recognized benchmarks, such as those summarized in Table 10, is crucial for market access and profitability.

7. Postharvest storage and preservation of sesame seeds

Characterized by a high oil content that can exceed 50% (Balouchi *et al.*, 2023), sesame seeds are consequently highly susceptible to quality loss during storage. Proper postharvest handling and storage are essential to preserve quality and protect the crop's economic value, given its wide uses from direct consumption and oil extraction to value-added products (Osei-Kwarteng and Ogwu, 2024).

7.1. Optimal storage conditions

Sesame seed quality depends heavily on storage temperature and relative humidity (RH) (Adebisi *et al.*, 2008). Lower temperatures prolong shelf life and reduce microbial and enzymatic activity (Gholamhosseini and Mansouri, 2024). Optimal storage is $4-10^{\circ}$ C, with further reduction (*e.g.*, 5°C at 40% RH) needed when RH exceeds 25% to prevent fungal growth and biochemical degradation (Sadeghi Germaroodi *et al.*, 2022). Continuous monitoring of temperature and humidity, plus adequate ventilation in bulk storage, is vital. Drying seeds to ≤6% moisture before storage is a critical step for preserving oil quality, as it lowers the seed's water activity to inhibit fungal growth and inhibits lipase enzyme activity, thereby preventing hydrolytic rancidity (Abdiani *et al.*, 2024)

7.2. Prevention of pest and fungal infestation

Post-harvest losses from insect infestation in sesame can be substantial, with key pests such as the red flour beetle (*Tribolium castaneum*) and the cigarette beetle (*Lasioderma serricorne*) causing direct weight losses that can range from 5% to over 20% under suboptimal storage conditions (Berhe *et al.*, 2023, 2024). Furthermore, fungal contamination, particularly by mycotoxin-producing species like Aspergillus flavus, poses a significant health risk (Khan, 2024). To mitigate these threats, fumigation with phosphine (generated from aluminium phosphide) is a widely adopted chemical control measure, which has demonstrated high efficacy, often exceeding 95–98% mortality against susceptible populations of major storage pests when applied at standard dosages (*e.g.*, $1-3$ g/m^3) for an adequate exposure period (Chaudhry, 1997; Nayak *et al.*, 2020). As a non-chemical alternative, gamma irradiation has also proven effective (Gholamhosseini and Mansouri, 2024). Research indicates that dosages between 0.5 and 1.0 kGy are sufficient for complete disinfestation of stored sesame seeds, while doses up to 5 kGy can control fungal growth without significantly compromising seed viability or oil quality (Hassan *et al.*, 2018; Al-Bachir, 2016).

7.3. Structural considerations

Structural storage practices are critical for maintaining seed quality by managing micro-environmental factors like moisture and pressure. Stacking bags directly on concrete floors, for instance, can lead to moisture wicking, potentially increasing the seed moisture content in the bottom layers by $2-3$ percentage points above the safe threshold, creating localized hotspots for fungal proliferation (Gebregergis *et al.*, 2024). Therefore, stacking on pallets with at least a 1 m clearance from walls is essential for preventing moisture transfer and promoting air circulation (Alemayehu *et al.*, 2023). Furthermore, excessive stack height exerts significant compression force on the lower bags. Studies on oilseeds have demonstrated that stack heights exceeding 3 meters can cause mechanical damage, leading to a reduction in germination capacity by as much as 10–15% in the bottom layers and an increase in free fatty acid content due to cracked seed coats (Abdiani *et al.*, 2024). Proper labelling and segregation of seed lots by harvest date and quality grade remain crucial for effective inventory management and preventing cross-contamination.

7.4. Impact on oil quality

Two key indicators of oil degradation during storage are free fatty acid (FFA) content and peroxide value (PV) (Anwar *et al.*, 2007). Increases in these indices indicate hydrolytic and oxidative spoilage, respectively, reducing crude oil quality, refining efficiency, and the flavour, shelf life, and safety of the final product (Tan *et al.*, 2017). Maintaining low seed moisture, avoiding mechanical damage, and preventing microbial growth are essential to preserve oil quality. Furthermore, the initial integrity of the capsule itself, a factor influenced by shatter resistance traits, can play a role by providing a natural physical barrier that protects seeds from environmental fluctuations and pest ingress prior to threshing, potentially contributing to better initial oil quality entering storage.

7.5. Special considerations

Dehulled sesame seeds are more prone to oxidative rancidity due to their increased surface area (Abou-Gharbia *et al.*, 1997); therefore, unhulled seeds are preferred for long-term storage. Processing delays should be minimised, and storage ideally conducted in hermetically sealed containers under controlled atmospheres when possible.

8. Challenges, innovations, and future directions in sesame harvesting and postharvest handling

Sesame production faces growing pressure for mechanisation and reduced postharvest losses, particularly from seed shattering (Myint *et al.*, 2020; Gholamhoseini, 2023; Gholamhoseini and Dolatabadian, 2024a). The biological complexity of capsule dehiscence and plant fragility make direct mechanical harvesting challenging. Progress in breeding shatter-resistant genotypes and refining harvest equipment has been notable but remains underutilised, especially in smallholder systems.

A major constraint is the mismatch between current cultivars and conventional combine harvester requirements, leading to high seed loss and reduced quality. Bridging this gap demands breeding ideotypes and engineering harvesters with sesame-specific adaptive components, requiring collaboration among agronomists, breeders, and engineers.

Future mechanisation will hinge on innovations that are both advanced and socioeconomically accessible. Promising developments–marker-assisted selection, AI-based harvest timing, optical seed sorters, and self-calibrating combines–remain out of reach for many low-input producers. Technologies must be efficient, affordable, adaptable to diverse agroecologies, and supported by local capacity building.

Postharvest quality management is equally critical. Without proper drying, handling, and storage, mechanised harvesting can cause contamination, discolouration, and oil quality loss. Standardised grading, operator training, and alignment with international quality benchmarks are essential for transforming sesame into a high-value crop.

Research priorities include high-throughput phenotyping for shattering traits, precision agriculture tools (drones, ground sensors) for harvest timing, and low-cost modular harvesters for smallholder fields in Africa, South Asia, and the Middle East. Novel strategies, such as bio-based capsule-strengthening agents or temporary surface coatings to reduce mechanical stress, also warrant exploration.

9. Conclusion

Sesame stands at a pivotal juncture, rich in nutritional value, ecological versatility, and economic promise, yet its full potential remains largely untapped. Addressing the technical challenges of seed shattering and mechanised harvesting is essential, but it is not sufficient. As this review has emphasised, sustainable expansion of sesame cultivation demands a systemic transformation that integrates genetic improvement, engineering solutions, and postharvest technologies within a broader socio-economic framework. Mechanisation must be coupled with robust seed systems, farmer-centred knowledge dissemination, infrastructure investment, and supportive institutional environments. Unlocking its future as a resilient, high-value crop requires nothing less than a holistic, inclusive, and strategic realignment of the entire production and value chain. Specifically for smallholder farmers, adopting such mechanisation-ready ideotypes could drastically reduce dependency on costly and often scarce manual labour, improve harvest timeliness, minimise post-harvest losses, and ultimately enhance profitability and resilience, facilitating their better integration into modern value chains. Realizing this potential will require targeted next steps, including establishing pilot breeding programs focused on these ideotypes, conducting participatory on-farm trials to validate performance across diverse environments, and fostering public-private partnerships to facilitate the co-development and dissemination of adapted machinery and cultivars.

Conflicts of interest

The authors declare no conflicts of interest related to this work. All authors confirm that there are no personal, professional, or financial relationships that could potentially influence the results or interpretation of this study. All co-authors have reviewed and approved this statement.

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