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Review Paper

The effects of storage conditions on phytochemical and bioactive compounds of garlic

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ABSTRACT

Garlic is a medicinal plant and seasoning herb with numerous properties. Varieties of garlic with red skin compared to cultivars with white skin, often show resistance to fungal diseases. Gene modification by gamma-ray increases the resistance of garlic against chastity and diseases. Heat treatment enhances the chemical properties of garlic, leading to the production of high-potency antioxidants. The quality of the manufactured product is related to the type and conditions of heat treatment. Manual harvesting of garlic reduces the quality of the product and increases production costs by 50% or even more, which results in receiving a product with low quality and high price. Garlic should be kept at a low temperature to prevent the germination and growth of fungi. Bacteria and viruses cause rot in onions and garlic, and hot water is an effective method to preserve garlic from nematodes without damaging the product, which is applied in certain conditions.

1. Introduction

Garlic (*Allium sativum* L.) is a monocotyledonous, herbaceous, perennial plant that belongs to the Allium family. It is native to South Asia, Central Asia, and northeastern Iran. The garlic production cycle is heavily reliant on the germination of seeds and bulbs. For optimal development, production, and yield, high-quality seed stock is essential. By utilizing healthy, disease-free garlic seeds, growers can establish a solid foundation for productive garlic cultivation (Anum et al., 2024). China dominates the global market, holding an impressive 73% share of production (Goldstein and Shemesh-Mayer, 2022). The quality of garlic seeds directly influences the production and financial success of garlic farms. Additionally, growers appreciate the ability of certain cultivars to reproduce from true seeds (Shemesh-Mayer and Kamenetsky-Goldstein, 2021).

Garlic has been grown for thousands of years and is globally valued not only as a culinary ingredient but also as a natural remedy for multiple health conditions. Extensive research confirms that garlic exhibits a wide range of health benefits, such as fighting cancer, reducing cholesterol, lowering blood pressure, protecting the liver, and regulating immune function—all thanks to its potent bioactive components (Seo et al., 2009).

The health benefits of garlic are largely determined by its bioactive constituents, particularly organosulfur compounds and thiosulfinates (Kim et al., 2012). Despite its many medicinal properties, garlic should be consumed in moderation, as excessive intake can lead to damage to the stomach and intestinal walls, cause anemia, and reduce protein and calcium levels (Amagase et al., 2001; Kim et al., 2012).

Garlic plants are sensitive to both drought and excessive moisture, with the latter causing root rot. Therefore, it is essential to manage watering carefully, avoiding re-watering until the field is in full bloom. Moisture stress can negatively impact the initial growth and multiplication of garlic, resulting in smaller bulbs at harvest. When applying nitrogen fertilizer in solution form, the amount should not exceed 300 kilograms. Excessive nitrogen can promote the growth of the plant's aerial parts while inhibiting adequate bulb development (Prahlad et al., 2022).

The aerial parts start to dry from the tip, and if the goal is to produce dried garlic, about 10 to 12 cm of the plant stem are left, and the rest of the stem is cut and then removed from the soil using a machine or shovel (Sari et al., 2024). To reduce its moisture, it is necessary to leave the garlic in the ground for one to two weeks.

Additionally, the pungent odor of raw garlic can permeate human skin, resulting in unpleasant body and oral odors. To mitigate or eliminate this undesirable smell while preserving or enhancing garlic's beneficial properties, various processing technologies, such as heat treatment or fermentation (also known as aging), have been employed in recent years (Bae et al., 2014). The quality of garlic is heavily influenced by the quality of the seeds and bulbs used for planting. Proper storage and transportation methods are crucial for maintaining both the quality and therapeutic properties of garlic. While traditional medicine and healthcare professionals recommend garlic consumption, it is important to note that exceeding a certain amount can pose risks to human health.

This study focuses on understanding how different storage conditions affect the beneficial compounds found in garlic and its products. Garlic is not just a flavorful seasoning but also a medicinal plant packed with health-boosting elements like organosulfur compounds and antioxidants. However, the way garlic is stored and processed can greatly impact its quality and effectiveness. In this research, we explore how factors like temperature, humidity, and processing methods—such as fermentation and heating—can help preserve or even enhance these valuable compounds. We also look at how using machines for harvesting and improved storage techniques can influence the

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final product's quality. Since manual harvesting is expensive and issues like fungal diseases and nematodes pose significant challenges, this study suggests modern solutions like genetic modification and controlled heating to improve storage and cut down on costs. Ultimately, the goal is to offer practical recommendations for producing top-quality garlic products more efficiently, especially in the East Azerbaijan region, which is a major garlic-growing area in Iran.

2. Garlic production in East Azerbaijan Province

Jihad Keshavarzi reported that the garlic cultivation area in East Azerbaijan Province spans 830 ha, yielding approximately 24,500 tons of the crop annually. While the average garlic production in other provinces in Iran is around 29 tons per ha, East Azerbaijan Province achieves a significantly higher yield of 53 tons per ha. The primary garlic-producing counties in the province include Azarshahr, Ajabshir, Malekan, and Bonab. In terms of garlic cultivation area, East Azerbaijan ranks sixth nationwide, while it holds the fourth position in terms of production volume.

Given the substantial costs associated with manual harvesting, which account for approximately 35% of total production expenses, the feasibility of adopting mechanized harvesting methods was thoroughly investigated. Interviews with farmers in the East Azerbaijan region, combined with economic analyses, demonstrated that mechanization could significantly reduce costs while enhancing product quality.

The yield of the crop depends on many factors and conditions, and in general, the yield of fresh garlic is between 20 and 30 tons and dry garlic is between 10 and 15 tons per ha, which for East Azerbaijan is about 22 tons fresh and 13 tons dry. The province cultivates a variety of garlic, including local garlic, pink garlic, red garlic, white garlic, and the Azar variety. The garlic varieties cultivated in the East Azerbaijan region are drying out as shown in Figure 1.

Figure 1. Various garlic cultivars in East Azerbaijan, Iran

3. Changes in garlic quality during fermentation under different conditions

Black garlic (BG), a fermented form of fresh white garlic (WG), is created through a controlled aging process involving elevated temperatures (40–90°C) and high humidity (60–90%) over 10 to 90 days. During this thermal treatment, complex biochemical reactions occur, including enzymatic browning and Maillard processes, which gradually turn the garlic from its original white or yellowish hue to a deep brown shade (Choi et al., 2014; Kimura et al., 2017).

The quality of the final product is influenced by the production conditions during heat treatment. It is recognized that BG contains more functional compounds than fresh garlic (Kimura et al., 2017). The heating process converts unstable, unpleasant, and pungent compounds in raw garlic into stable and tasteless ones. This transformation involves the modification of allicin, which is responsible for garlic's characteristic odor and taste, and results in the production of water-soluble antioxidants such as S-allyl cysteine (SAC), biologically active alkaloids, and flavonoids (Kang, 2016; Kimura et al., 2017). Research suggests that SAC in BG may help reduce oxidative damage and lower the risk of various diseases, including cardiovascular issues, cancer, stroke, Alzheimer's disease, and other age-related degenerative conditions (Ryu and Kang, 2017).

Garlic is rich in free amino acids, which play a crucial role in the Maillard reaction during the heat treatment of raw WG. This process enhances protein digestibility in food and increases its nutritional value. Researchers have found that the cysteine content in BG samples is significantly higher than that in WG (Sasmaz et al., 2022). Additionally, several studies indicate that the carbohydrate content in BG can increase by one to two times compared to WG (Ryu and Kang, 2017). Research data demonstrate that the fermentation process alters the chemical composition of garlic and enhances the bioactivity of BG (Sasmaz et al. 2022).

The heating process of garlic results in the formation of biological compounds, such as phenolics (Kim et al., 2013; Molina-Calle et al., 2017). The concentration of phenolic compounds in BG is closely linked to the selective fermentation method used. One study found that the phenolic acid content in BG increased by more than five times compared to raw WG (Kim et al., 2013). Another study identified the optimal conditions for BG production as 70 °C, 90% relative humidity, and a fermentation period of 21 days (Zhang et al., 2016). The optimal conditions for BG production in the present study were maintained at a consistent temperature and relative humidity, but the fermentation period was extended to 24 days. This extended duration can be attributed to the specific type of garlic cultivars used. In Iran, the high production costs of BG are attributed to a lack of expertise and adequate facilities. Consequently, only a specific segment of the population—primarily affluent individuals and those prescribed by doctors—tends to consume it. Furthermore, the limited promotion of the properties and benefits of this processed product means that many people remain unaware of its unique advantages.

The quality of the conversion depends on the type and conditions of the operation, which in any case will improve the properties of raw garlic; but if it is carried out under optimal conditions, this amount will reach its maximum value. In this operation, the amount of protein, carbohydrates, phenolic acids, antioxidants, etc. increases. BG has a dark brown color and is tasteless (Herlina et al., 2019).

4. Garlic harvesting machines

One significant drawback of existing garlic harvesting machines is that they place the harvested crop on the soil surface after pulling. This process requires improvement, as garlic must be air-dried after being harvested. Effective air drying is crucial for enhancing the quality and shelf life of the crop (Nahmgung et al., 1995). Air-drying garlic naturally is often preferred because it better preserves the garlic's quality and beneficial properties. This method involves a slow, gradual process in an ambient environment, which helps retain essential compounds such as allicin—a key component known for its antimicrobial and antioxidant properties. Additionally, natural air drying maintains the garlic's authentic flavor and aroma more effectively, as the gentle drying process minimizes unwanted chemical alterations. Unlike industrial methods, natural drying does not rely on additives or chemical treatments, resulting in a purer and healthier product. Furthermore, this approach reduces the risk of contamination, as it eliminates the need for machinery or equipment that could introduce impurities. From an environmental perspective, air-drying garlic is more sustainable, as it consumes less energy compared to industrial drying processes. In contrast, industrial drying often employs high heat, which can degrade beneficial compounds and necessitates the use of additives, despite offering advantages such as faster drying times and precise moisture control. Overall, natural air-drying is widely regarded as superior for preserving the quality and properties of garlic.

In cold regions, garlic typically develops larger and heavier cloves due to the extended growing season and cooler temperatures, which allow the plant to absorb more nutrients. The skin of garlic grown in these regions is darker and tougher, serving as a protective layer against harsh cold weather. Additionally, garlic from cold climates tends to have a stronger flavor and aroma, as the challenging growing conditions stimulate the production of aromatic compounds like allicin. These garlic varieties are also richer in nutrients and exhibit higher antimicrobial and antioxidant properties. In contrast, garlic cultivated in temperate regions usually has smaller and lighter cloves, as the shorter growing season and milder temperatures promote faster growth. The skin of these garlic bulbs is lighter and smoother, and they possess a milder flavor and aroma, making them more versatile for use in a wide range of dishes.

These differences highlight how environmental conditions can significantly influence the quality and characteristics of garlic. Garlic from cold regions, with its robust flavor and higher nutrient content, is ideal for dishes that require a pronounced aroma and taste. On the other hand, garlic from temperate regions, with its milder flavor and softer skin, is better suited for everyday use and lighter dishes. Selecting the appropriate growing region not only enhances the quality of the garlic but also contributes to its diversity and market appeal. This underscores the importance of considering environmental and soil conditions in garlic cultivation, as these factors directly impact the health benefits and satisfaction of consumers.

Crop physical characteristics play a key role in designing farm equipment. To advance mechanized garlic harvesting, studies have examined the morphological and optical traits of garlic bulbs at harvest time. These investigations employ specialized tools like universal testing machines (UTMs) and precision timing devices for accurate measurement and analysis (Atif et al., 2020). The materials used in machinery construction or their properties can alter the appearance of garlic, potentially affecting its performance (Park et al., 2024). Understanding the geometric properties of garlic before harvesting is crucial for developing machinery that effectively separates soil, controls factors, and manages by-products from the crop (Park et al., 2024).

The characteristics and weight of garlic are key design factors in optimizing the mechanical model of the harvesting machine (Søgaard and Sørensen, 2004), analyzing germination performance (Park et al., 2024), and creating machines suitable for various garlic varieties and regions. Among the geometric properties, volume has been identified and examined as a significant heat transfer characteristic in the drying of agricultural products (Zhu et al., 2021). Therefore, the physical characteristics of crops must be carefully considered in the development of agricultural machinery.

Garlic cultivation and harvesting methods vary significantly from region to region, with plastic mulching presenting challenges for mechanization. Warm-season garlic (WSG) is typically harvested by hand, which allows for shallower planting of seeds. In contrast, cool-season garlic (CSG) requires a deeper planting depth (Park et al., 2024). The physical properties of garlic are generally influenced by soil and climate characteristics. Soil properties, along with meteorological and climatic factors, impact the physical and chemical properties of the crop (Moon et al., 2017).

Implementing mechanization in garlic cultivation, particularly during the harvesting phase, can significantly reduce production costs—sometimes by as much as half. Additionally, the quality of the garlic produced remains consistent, allowing it to be introduced to the market at a higher price. The type of machinery and the materials used in its components can influence the color and quality of the garlic. To ensure product quality, it is essential to conduct a series of tests and compare the results with established standards.

5. Measurement of mechanical properties

The compression test on garlic is conducted using a universal testing machine (UTM) to measure the Poisson's ratio (Figure 2). The transverse and longitudinal deformations of the initial conditions are utilized to calculate the Poisson's ratio. The elastic modulus is determined using Hertzian contact theory. The Poisson's ratio and elastic modulus are calculated using Eq. (1) (Park et al., 2024)

$$\mu = \frac{\Delta D/D}{\Delta L/L} = -\frac{\varepsilon'}{\varepsilon} \tag{1}$$

where μ is the Poisson's ratio of the garlic, ΔL is its longitudinal deformation, L is its length, ΔD is the transverse deformation of the beam, D is the transverse deflection, ε is the longitudinal strain of the beam, and ε′ is the transverse strain of the beam. The elastic modulus of the garlic (E) is obtained using Eq. (2)

$$E = \frac{0.8255^{3/2} \times F(1-\mu^2)}{\varepsilon^{3/2} \times R^{1/2}} \tag{2}$$

where R is the width of the garlic, and F is the force applied to the samples. The allowable compressive stress of the garlic was obtained by applying the modulus of elasticity according to Hooke's law. The compressive stress was calculated using Eq. (3)

$$\sigma = E\varepsilon \tag{3}$$

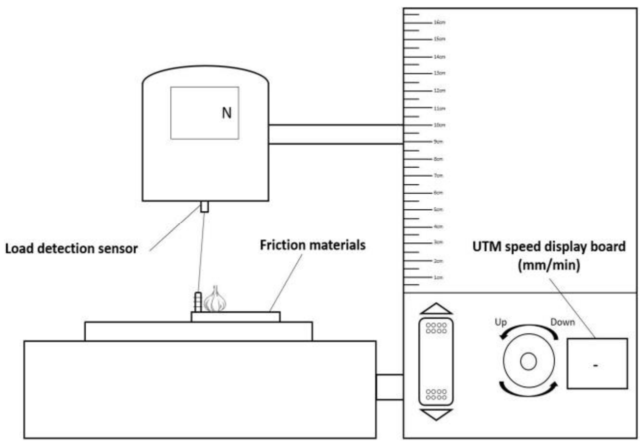

Figure 2. Schematic diagram of measuring the garlic friction coefficient using UTM

where σ is the compressive stress of the surface. The coefficient of static friction for each material was calculated using Eq. (4)

$$\mu s = \tan \theta \quad (4)$$

where μs is the coefficient of static friction. θ is the angle of the friction material.

6. Conditions of storage

Garlic requires appropriate storage conditions to maintain its relatively long-lasting quality. Excessively high temperatures can lead to tuber shrinkage, while high humidity creates an environment conducive to the growth of fungi and molds, as well as stimulating the development of shoots and roots. One common method for storing fresh agricultural products is to keep them at low temperatures, which can enhance their shelf life and quality. Storing garlic seeds at low temperatures helps reduce water loss from the tubers, maintain a consistent respiration rate, and lower the metabolic rate. Potential damages from improper storage include reduced water content, shoot growth, rotting, and softening (chilling injury) (Nurmalia et al., 2019). Figure 3 shows examples of damages by inadequate storage conditions.

To store garlic and preserve its quality and shelf life, the ideal conditions include a temperature range of 0 to 4 °C, a relative humidity of 65-70%, good ventilation, low light exposure, and the use of suitable storage containers such as mesh bags or open baskets. These conditions help prevent sprouting, inhibit the growth of fungi and mold, and maintain the natural flavor and aroma of garlic. Additionally, storing garlic in a dark environment, away from direct sunlight, prevents quality degradation and slows down the germination process. By adhering to these guidelines, the quality and shelf life of garlic can be extended significantly, reducing the risk of spoilage. These practices have been unanimously confirmed by farmers and agricultural engineers. Temperature and humidity are important factors in reducing quality and providing a breeding ground for fungi and bacteria. These two parameters play a fundamental role in the storage and preservation of garlic, and it is necessary to approach this issue with greater sensitivity.

7. Preharvest diseases of garlic

7.1. Garlic bulbs as habitat pathogens

Ensuring robust seed production requires proactive disease prevention in garlic cultivation. Garlic crops face numerous pathogens that compromise yield quantity, bulb integrity, and resistance to further infections. Through systematic phytosanitary measures, producers can preserve crop vitality and minimize pathogen carryover between growing cycles. Such protective protocols enhance agricultural output consistency while supporting the ecological balance of continuous cultivation systems. Garlic bulbs are larger than the seeds of most other crops, and storing them at temperatures between 10 and 14 °C makes disease control challenging (Nikitin et al., 2023). Consequently, the use of fungicide dips does not guarantee a significant reduction in inoculum in the planting stock, unlike for most major seeds (Gálvez and Palmero, 2022). Additionally, infestations of wheat mites and onion mites during storage can lead to garlic rot. The conditions favorable for fungal growth also promote the proliferation of mites (Jeffers and Chong, 2021). Figure 4 illustrates the garlic production cycle.

Figure 3. Garlic seed damage in adverse conditions

Figure 4. Garlic production cycle

The quality of the seeds planted directly affects the quality of the harvested garlic crop. Therefore, it is essential to take basic precautions to preserve the seeds and bulbs before planting. Garlic is a sensitive seed, and due to temperature conditions, the use of fungicides is not always 100 % reliable, which means there is always a risk of contamination in the garlic storage warehouse. Careful control of storage conditions is necessary to prevent potential damage from rot and to maintain seed viability.

7.2. Fungal pathogens

Garlic seed production is vulnerable to fungal infections. Several diseases, including bulb rot and leaf spots, can be caused by pathogens including *Fusarium*, *Penicillium*, and *Alternaria*. These microorganisms can remain dormant and grow in storage media and infect garlic bulbs before planting or during storage. Effective disease management techniques depend on a thorough understanding of the symptoms and damage caused by fungal infections. *Aspergillus ochraceous*, *Aspergillus niger*, *Penicillium hirsutum* Dierckx, and *F. proliferatum* Nirenberg are the main fungi that attack garlic bulbs during storage (Dugan et al., 2007).

White rot is a serious threat to garlic agriculture, causing significant losses and persistent soil contamination. Given the economic and environmental consequences, some regions have implemented strict seed quarantine protocols. These measures aim to limit the spread of the pathogen, protect garlic crops, and ensure agricultural sustainability. This preventive approach to disease management protects garlic-growing communities from the devastating effects of white rot (Yimer, 2020).

7.3. Mycotoxin

It is essential to identify fungi capable of producing toxins, especially since *F. verticillioides* has recently been recognized as a pathogen responsible for garlic rot (Dugan et al., 2007). Fumonisins are primarily produced by *F. proliferatum* and *F. verticillioides*, with *F. proliferatum* also generating other mycotoxins (Figure 5) (Anum et al., 2024; Munkvold, 2017).

7.4. Bacteria and viruses

A garlic disease known as "maladie café au lait" is caused by the pathogen *Pseudomonas* fluorescens, attributed to Migula. This disease poses a significant threat to garlic cultivation, impacting both yield and quality (Jacques et al., 2009). Several organisms, including *E. chrysanthemi*, *Erwinia carotovora*, *Enterobacter cloacae*, *Pseudomonas gladioli*, and *Burkholderia*, can cause soft rot in onions and garlic. However, these organisms tend to inflict more damage on onions than on garlic (Akar et al., 2019). Additionally, multiple viruses can be present in what is referred to as a mixed infection (Lunello et al., 2007). These include garlic mite-borne filamentous virus (GarMbFV), garlic virus A (Gar V-A), garlic virus B (Gar V-B), garlic virus C (Gar V-C), garlic virus D (Gar V-D), garlic virus E (Gar V-E), and garlic virus X (Gar V-X) (Mavrič and Ravnikar, 2005).

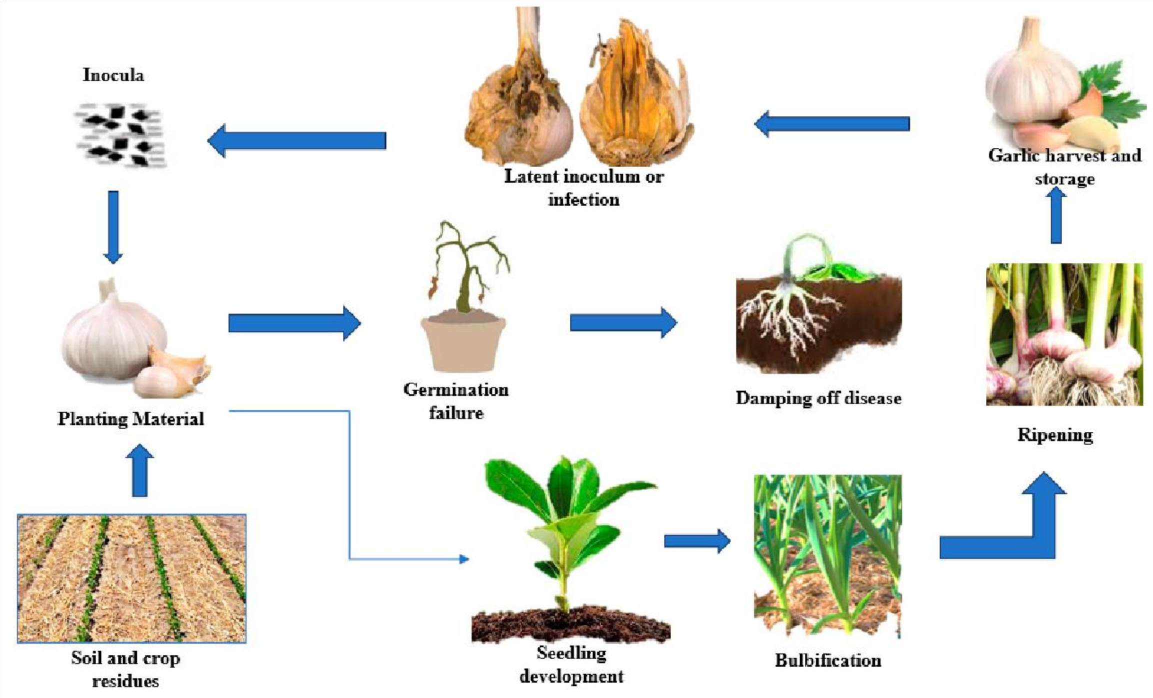

Figure 5. Fusarium dry rot cycle in garlic

7.5. Nematodes

Nematode infections, particularly those caused by *Ditylenchus dipsaci*, pose significant challenges for garlic seed growth. These small roundworms attack the roots, bulbs, and leaves of the garlic plant, altering the shape of the bulbs and reducing yield. Garlic seeds infested with nematodes can accelerate their spread in subsequent harvests and exacerbate damage. Effective nematode management is crucial for maintaining healthy seeds (Yu et al., 2010; 2012).

Nematode populations in garlic seeds have been managed through hot water treatments. This method effectively kills nematodes without harming the garlic by immersing the cloves or bulbs in hot water at a specified time and temperature. Hot water treatments can reduce nematode populations and help prevent the transmission of nematode-borne diseases to future crops. Different garlic cultivars exhibit varying abilities to tolerate higher temperatures without damage. Therefore, it is essential to identify a temperature that is high enough to kill the nematodes while minimizing serious damage to the garlic plants (Draghici et al., 2022; El-Saadony et al., 2021). Table 1 presents examples of fungal pathogens affecting garlic seed.

It is essential to plant healthy seeds that are free from diseases and pests, because infected garlic seeds can be transferred to subsequent harvests. Hot water is used to control nematodes, which is a very good and excellent method that has yielded satisfactory results. In this method, water temperature and dwell time are critical parameters that must be managed to prevent damage to the garlic.

8. Garlic harvesting procedure

The stalks of garlic, which are cut during harvesting, are often regarded as waste. During this process, garlic stalks are trimmed in the field while the bulbs are collected. Currently, the collection of dried garlic is done by hand, and a study indicated that labor costs account for 50.9% of total production costs (Park et al., 2024). Therefore, further research into the mechanization of garlic collection is essential to enhance the competitiveness of garlic production and address the challenge of high labor costs.

Table 1. Fungal pathogens of garlic seeds

Nematode pest	Common name	Signs of injury	Reference
Meloidogyne spp.	Root-Knot Nematode	Galls on roots, stunted growth, nutrient deficiency	Ravindra et al. (2015)
Tylenchulus semipenetrans	Citrus Nematode	Feeding damage on roots, decline in plant health	Amin and Youssef (2014)
Longidorus spp.	Needle Nematode	Stunted growth, root damage, nutrient deficiency	Ravindra et al. (2015)
Trichodorus spp.	Stinging nematode	Feeding damage on roots, reduced root system	Anum et al. (2024)
Pratylenchoides spp.	False root nematode	Root scarring, growth arrest, yield reduction	Yavuzaslanoglu et al. (2019)

According to interviews with farmers in East Azerbaijan regarding the costs associated with garlic production, from planting to harvesting, all farmers, without exception, expressed concerns about the high costs of harvesting, noting that approximately 35% of production expenses are attributed to this stage. Therefore, the mechanization of garlic harvesting is essential for enhancing competitiveness and reducing labor costs. Transitioning from traditional to mechanized harvesting methods will improve efficiency and lower overall production costs. This change is likely to increase profits for farmers while also slightly reducing market prices. Figure 6 shows the separation of garlic stalks.

9. Resistant garlic varieties

In East Azerbaijan province, two varieties of garlic—red-skinned and white-skinned—are cultivated, each comprising different cultivars. However, their cultivation is limited due to the province's harsh climate. Generally, red-skinned garlic varieties exhibit greater resistance to pathogens such as fungi and viruses compared to white-skinned varieties. This enhanced resistance can be attributed to several factors.

Figure 6. Separating garlic stalks

Firstly, red-skinned garlic typically contains higher levels of phenolic and antioxidant compounds, which play a crucial role in neutralizing free radicals and protecting plant tissues from damage caused by pathogens. Secondly, the skin of red-skinned garlic is usually thicker and more robust, serving as a stronger physical barrier that prevents the penetration of fungi and viruses. Additionally, red-skinned garlic may contain specific allium compounds with potent antifungal and antiviral properties, which inhibit the growth and reproduction of pathogens. Moreover, red-skinned garlic tends to have higher concentrations of allicin, a sulfur-containing compound known for its strong antimicrobial properties, further enhancing its resistance. Lastly, genetic differences between red- and white-skinned garlic varieties may contribute to the production of more defense-related compounds or the activation of more robust resistance mechanisms in red-skinned garlic. Collectively, these factors function as defense mechanisms, making red-skinned garlic more resistant to infections and diseases than its white-skinned counterpart. A study showed that red-skinned garlic varieties often showed stronger resistance to Embellisia allii than white-skinned varieties (Dugan, 2007).

10. Genetic modification

Particle bombardment, i.e., biotransformation, can transform garlic using plasmid DNA (Khar et al., 2020; Parreño et al., 2023). This method has significant implications for the transfer of resistance genes in garlic. Gamma irradiation has been proposed as a method for inducing beneficial mutations in garlic, potentially leading to disease resistance (Figure 7) (Gultom et al., 2020).

11. Conclusion

By examining different storage methods in controlled, fermentation and thermal processing, it is clear that these techniques can significantly improve the quality and shelf life of garlic products. For example, BG produced from garlic fermented at high and controlled temperatures contains high levels of antioxidants and bioactive compounds such as SAC compared to cream. These findings become useful as optimization of storage and processing conditions can help maintain and even enhance the properties of garlic.

In addition, the present study highlights the economic and operational challenges of garlic farmers, especially in cold garlic regions such as East Azerbaijan. The results show that garlic harvesting is not only costly but also accounts for about 35% of the total production costs. The use of mechanized methods and advanced storage can reduce these challenges and improve product quality. Also, methods such as genetic modification and gamma irradiation have been proposed as new solutions to increase garlic resistance to diseases and improve product performance. These methods not only reduce production costs but also help produce a higher quality and more resistant product.

Finally, this research draws a map for farmers and garlic industry activists by providing practical solutions such as the use of mechanization, storage in controlled environments, and genetic improvement. By applying these strategies, we can produce high-quality garlic products that meet the needs of consumers and market standards. This will not only help develop the garlic industry in cold-growing regions such as East Azerbaijan but can also be a model for other garlic-producing regions around the world.

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Competing interests

No competing financial interests or personal relationships are known to the authors that could have influenced this study.

Data availability statement

No original data were used in this review study.

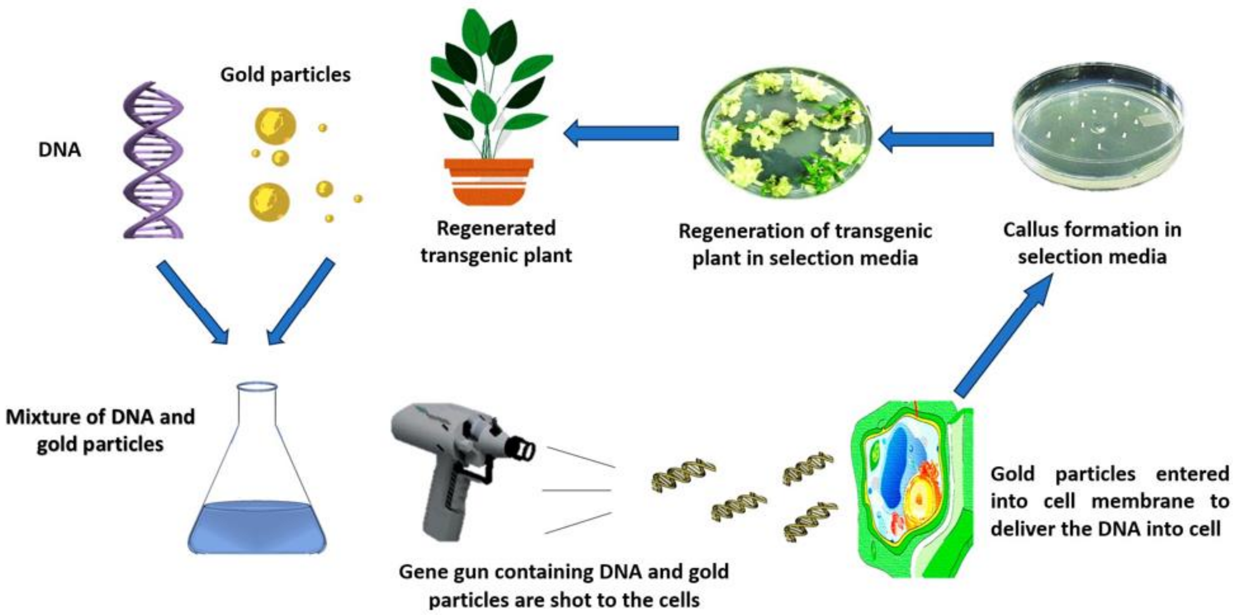

Figure 7. Particle bombardment for genetic transformation

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