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Advancing Vegetable Grafting: A Comprehensive Review of Techniques, Challenges, and the Future of Automated Solutions

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Vegetable grafting, a practice that combines two plant parts rootstock and scion into a single, superior plant, is an increasingly important technique in modern agriculture. By enhancing yields, stress resistance, and disease tolerance, grafting plays a crucial role in addressing challenges such as soil borne pathogens, extreme environmental conditions, and crop vulnerability to nematodes. Despite its benefits, vegetable grafting faces several challenges, including the need for compatible plant material, labour-intensive nursery production, high seed costs, and the potential for pathogen spread. Effective grafting requires meticulous selection of rootstock and scion, precise grafting techniques, and optimal post-grafting care to ensure survival and success. Looking toward the

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future, significant advancements in grafting technologies and nursery practices are required to overcome these challenges and improve efficiency. The development of grafting robots, capable of mechanizing the grafting process, holds promise for increasing productivity while reducing labor costs. Additionally, the establishment of specialized plug plantlet nurseries, equipped with advanced seeders, growth chambers, and acclimatization facilities, offers a pathway to enhance seedling vigour and uniformity in developing countries. Future research should also focus on refining seed-priming methods, improving seedling storage technologies, and exploring digital tools such as databases, crop models, and mobile applications to optimize grafting practices. These innovations could provide valuable insights for growers, helping them select the best rootstock-scion combinations and manage crops more efficiently. With continued research and technological advancements, vegetable grafting is poised to become a global solution, offering sustainable growth and productivity improvements in agriculture.

Keywords: Stress; vegetable grafting; rootstock-scion; sustainable; productivity.

1. INTRODUCTION

Grafting, a time-honored horticultural technique, is widely used to bolster vegetable crop production. The essence of this technique lies in replacing the root system of an economically valuable cultivar, which may be susceptible to various environmental effects, with a more vigorous and robust plant. In the context of this practice, the newly introduced root system is referred to as the rootstock, and the top part of the plant, which holds economic value or interest, is known as the scion (Davis et al., 2008). The historical roots of vegetable grafting can be traced back to Japan in the late 1920s. During this period, watermelon (*Citrullus lanatus* L.) plants were ingeniously grafted onto *Lagenaria siceraria*, specifically to guard against L. fusarium wilt, a move credited to Kawaide in 1985. Since that pioneering effort, the practice of grafting has proliferated worldwide. In fact, in contemporary Japan and Korea, approximately 92% and 95% of the total area under watermelon cultivation respectively, employs grafted seedlings (Lee et al., 2010; Arvanitoyannis et al., 2005).

The benefits of grafting extend beyond mere protection against biotic stress from root-knot nematodes (Louws et al., 2010; Yin et al., 2015) and soil-borne fungi (Crinó et al., 2007, Aydinli et al., 2019). It has emerged as a valuable agricultural practice for managing various abiotic stresses, such as those caused by drought (Albacete et al., 2015; Schwarz et al., 2010) and cold (Li et al., 2015). The application of grafting is primarily aimed at enhancing the production efficiency and resource utilization of vegetable crops, particularly in protected crops. The acceptance and adoption of grafting as a standard practice are largely dependent on the establishment of appropriate grafting methods and the successful development of vigorous rootstock through selective breeding (King et al., 2010; Colla et al., 2017). However, despite its many advantages, not all vegetable species are suitable for grafting due to considerations such as genetic compatibility, specific growth conditions, and the physiological and biochemical influences that could impact the success of grafting (Goldschmidt, 2014). In the global context, vegetable grafting is witnessing increasing popularity, particularly with cucurbits, tomatoes, eggplants, and peppers. The strategic use of vigorous and disease-resistant rootstocks ensures adequate yields in regions where various biotic and abiotic stressors limit productivity (Buller et al., 2013).

1.1 Cucurbitaceae

In the horticultural world, grafting is a common practice that is frequently applied to a variety of cucurbit species, particularly including watermelon, melon, and cucumber (Mohamed et al., 2014). This technique of combining two plants offers many commercial applications, making it a prevalent method in the agriculture industry. Grafting cucurbit plants involves numerous methodologies for the successful joining of the scion, or the plant that provides the fruit, and the rootstock, which offers the root system and lower stem. The procedures are typically carried out at the young seedling stages for optimal success, as noted in the research (Mohamed et al., 2014; Nicoletto et al., 2012). In order to make this process more efficient and cost-effective, there is potential for high-performance automation methods. These could involve either the assistance of operators or complete robotic control, which can significantly reduce the overall costs associated with producing grafted seedlings (Comba et al., 2016).

1.2 Solanaceae

Eggplant, tomato, and sweet pepper species are particularly amenable to grafting, a fact that is likely connected to their inherent regenerative capabilities. Grafting, as a horticultural practice, involves the joining of two plant species to leverage the strengths of both. In the context of these solanaceous crops, almost all greenhouse tomatoes and a significant proportion of eggplants are subject to grafting (Flores et al., 2010). However, the practice of grafting sweet peppers is less commonly adopted by producers, despite the fact that sweet peppers demonstrate compatibility with a variety of other solanaceous species. This lack of widespread adoption could be attributed to a range of factors, including the need for more specialized knowledge or equipment, or simply a lack of awareness of the potential benefits (Gebologlu et al., 2011).

Looking forward, there are several key areas that need to be addressed to increase the yield of solanaceous crops through grafting. The development of resistant rootstocks is one such area. These rootstocks need to be able to withstand a wide variety of diseases, a factor that is pivotal in ensuring the long-term success of the grafted plants. Furthermore, the root strength of the grafting plant plays a crucial role (Kawaide, 1985). Without sufficient root strength, the plant may struggle to support both its own growth and that of the grafted species. High compatibility between the two plant species is also vital to ensure that the grafting process is successful. Finally, the adoption of appropriate grafting methods is essential. This means that the techniques used should be suitable for the specific species involved, taking into account their unique characteristics and requirements. By focusing on these areas, there is the potential to significantly increase the yield of solanaceous crops through grafting.

2. HISTORY OF VEGETABLE GRAFTING

Grafting is the art of connecting two plant parts—a rootstock and a scion—through tissue regeneration. The end result is a physically unified plant that grows as a single entity (Janick, 1986). While this practice has existed for centuries, it is relatively new in vegetable cultivation. References to fruit grafting can be found in the Bible and ancient Greek and Chinese literature, indicating that the technique was in use in Europe, the Middle East, and Asia by the 5th century BC (Melnyk and Meyerowitz, 2015). Natural grafting is common in nature, and the observation of these natural grafts likely inspired the use of this technique in horticulture thousands of years ago (Mudge et al., 2009). The scientific application of grafting to vegetables first emerged in Japan and Korea in the late 1920s. This involved grafting watermelon onto gourd rootstocks to prevent soilborne diseases (Ashita, 1927; Yamakawa, 1983). Agricultural extension workers disseminated this new technique to farmers in Japan and Korea. By the early 1930s, the commercial use of grafted transplants had begun in Japan. This involved grafting watermelon onto bottle gourd (*Lagenaria siceraria* Mol.) and summer squash (*Cucurbita moschata* Duch.) to induce resistance to Fusarium wilt (Oda, 2002; Sakata et al., 2007, 2008).

The practice of grafting cucumbers, a process designed to reduce the impact of soilborne diseases and enhance the vigour of the scion, is believed to have its roots in the 1920s. Despite its origins in this decade, it was not until the 1960s that this approach saw commercial application, as noted by Sakata et al. in 2008. Within the family of Solanaceae crops, aubergine, or *Solanum melongena* L., was the first to be grafted onto scarlet aubergine (*Solanum integrifolium* Lam.), a process that was introduced in the 1950s (Oda, 1999; Mohanta et al., 2015). Following this, the practice of grafting tomato plants, or *Solanum lycopersicum* L., was initiated in the 1960s (Lee and Oda, 2003). The 1950s marked a significant shift in agricultural practices with the rapid development of protected cultivation. This involved the use of greenhouses or tunnels to enable offseason vegetable production and more intensive cropping patterns. Such advancements led to changes in existing crop rotation systems, causing farmers to become increasingly reliant on grafting as a means of controlling soilborne pathogens and other pests (Kubota et al., 2008; Lee et al., 2010). The scientific community began to invest in studies on developing effective rootstocks in the 1960s, notably in Korea. This saw significant results by 1990, with the proportion of grafted Solanaceae and Cucurbitaceae crops (including cucumber, melon, aubergine, and tomato) reaching 59% in Japan and 81% in Korea (Lee, 1994). Today, the majority of cucurbits cultivated in greenhouses are grafted in countries such as China, Japan, Korea, Turkey, and Israel. Furthermore, grafted vegetables have found commercial success in over 20 countries worldwide, demonstrating the global adoption of this effective agricultural technique.

3. IMPORTANCE OF VEGETABLE GRAFTING

3.1 To attain Resistances/Tolerances against Soil Borne Disease and Pest

In a comparative study, *Solanum torvum* was observed to have a higher level of resistance than *S. sisymbrifolium* when exposed to *V. dahliae* on soil that was both fumigated and infested with Verticillium (Çürük et al., 2009). In a similar vein, hybrid squashes, specifically those of the species *Cucurbita maxima* Duchesne × *Cucurbita moschata* Duchesne, which are widely utilized as rootstocks for melon, demonstrated a high degree of resistance to the debilitating effects of fusarium wilt (Reyad et al.,2021). Moreover, they showed a remarkable level of tolerance to a variety of other diseases, including verticillium wilt, monosporasus sudden wilt, and gummy stem blight. In addition, in soil that was infested with nematodes, *Cucurbita maxima* was found to be highly resistant to *M. incognita* thereby further exemplifying its robustness and suitability for cultivation in challenging conditions (Aydinli et al., 2019).

3.2 To Gain Tolerance to Abiotic Stresses

Savvas et al. (2011) has investigated grafting a popular tomato hybrid onto new rootstocks 'Beaufort', 'He-Man', and 'Resistar', evaluating its impact on plant growth, yield, and fruit quality. Growth rate and health, the number and consistency of fruits, and their texture, taste, size, weight, and colour are assessed. Tests are conducted under low to moderate salt-stress conditions, reflecting increased soil salinity worldwide. The study also explores grafting's impact on watermelons, showing enhanced tolerance to saline water and flooding. The findings could improve crop resilience and productivity in commercial agriculture. Grafting brinjal onto heat-tolerant brinjal rootstock appears promising, resulting in a prolonged growth stage and up to a 10% increase in yield (Rakha et al., 2019). In low temperatures, cucurbit crops do not germinate, making grafting useful for off-season crops (Singh et al., 2014). Grafted watermelon seedlings have higher antioxidants and antioxidative enzyme activities in their leaves under low temperature stress compared to self-rooted watermelon seedlings (Mohamed et al., 2018).

Intergeneric grafting enhances the flood tolerance in cucurbits. Flooding is known to have a detrimental effect on many plant physiological processes. More specifically, it reduces the photosynthetic rate. It also negatively impacts stomatal conductance, which is vital for the regulation of gas exchange and water vapor. Additionally, flooding can decrease transpiration rates. Furthermore, soluble proteins, which play a crucial role in plant growth and response to environmental stresses, are also reduced (Striker, 2012). However, these adverse reactions are significantly minimized when intergeneric grafting is applied. This is done by grafting a flood-tolerant bitter melon onto a flood-resistant rootstock. This not only bolsters the plant's flood tolerance but also allows it to thrive in conditions that would typically be detrimental. The fusion of these two species through grafting results in a plant that possesses the beneficial attributes of both, leading to improved resilience and productivity in flood-prone environments (Liao et al., 2001).

3.3 Improve Vigour and Yields

Grafting has proven to be quite beneficial when applied to the production of eggplants. One of the most advantageous combinations has involved grafting eggplants onto interspecific eggplant hybrids, notably the *Solanum incanum* (SI) × *Solanum melongena* (SM). This specific grafting combination has resulted in increased vigor and a high compatibility between the rootstock and scion, two critical factors for successful grafting. This combination has led to significant improvements in early and total yields of the eggplant crop. Furthermore, this method does not seem to have any adverse effects on the fruit's quality or composition, making it an optimal choice for eggplant producers. The benefits of grafting are not just limited to eggplants. Tomato plants, when grafted onto rootstocks like 'Efialto', 'Heman', and 'Maxifort', show a marked increase in their marketable yield (Djidonou et al., 2017). In addition, these particular rootstocks also enhance the lycopene content of the tomatoes, a highly desirable trait since lycopene is a powerful antioxidant.

In the case of melons and watermelons, grafting these plants onto different Cucurbita hybrids, specifically *C. maxima* × *C. moschata*, as rootstocks, has resulted in significantly higher yields. On average, the yield of melon plants has increased by 44% and that of watermelon plants by a staggering 84%, compared to the yields of the non-grafted plants (Martin, 2017; Hollick, 2021). The advantages of grafting extend to post-harvest traits as well. Watermelons, when grafted onto different rootstocks, have shown an increase in fruit firmness, a desirable trait that directly impacts the shelf life of these fruits. This improvement in quality ensures that watermelons remain fresh for longer periods, thereby reducing waste and increasing profitability for producers (Fallik et al., 2020).

3.4 Progressing Quality Characteristics

The type of rootstock used in the cultivation process can greatly affect the overall qualities of a watermelon, including its flavour, pH level, sugar content, colour, carotenoid concentration, and texture. These factors are crucial in determining the taste and nutritional value of the fruit. This is because the rootstock, being the foundation of the plant, plays a significant role in the absorption and distribution of nutrients (Fallik et al., 2020). In addition to watermelon, different rootstocks have also been found to have a profound influence on the quality attributes of grafted cucumbers (Tan et al., 2022). The fruit shape, skin and flesh color and texture, hardness, smoothness, rind thickness, and the quantity of soluble solids - all these factors can be manipulated through the choice of rootstock. This highlights the importance of selecting the right rootstock in order to obtain produce with desirable characteristics.

3.5 Effect of Grafting on Flowering and Harvest

According to Sakat et al. (2007), watermelon grafted onto bottle gourd rootstocks leads to earlier formation of female flowers compared to other rootstocks. However, cucumber varieties grafted onto a squash interspecific hybrid rootstock inhibit flowering. Grafting can influence flowering and harvest by improving the overall health and vigour of the plant. Grafted vegetables often exhibit earlier and more uniform flowering, leading to a more synchronized harvest. Additionally, the rootstock can enhance nutrient uptake, which may result in higher yield and better fruit quality. However, the effect on flowering and harvest timing can vary depending on the compatibility and characteristics of the rootstock and scion used.

4. IMPORTANT PRE-REQUISITES FOR VEGETABLE GRAFTING

Grafting is a critical horticultural technique in vegetable production that involves merging two distinct plant varieties to form a new, improved plant. This process enables growers to integrate desirable characteristics from each variety, like disease resistance, increased yield, or enhanced environmental tolerance, into a single plant. Grafting involves the union of two main components: the rootstock, or the lower part of the plant, and the scion, or the upper part. The rootstock usually supplies the roots for the new plant, while the scion provides the above-ground parts, like stems, leaves, and fruit (Garner, 2013). However, grafting can be complex and requires certain prerequisites to succeed, as shown in Fig. 1. These include plant compatibility for grafting, appropriate environmental conditions, and the correct technique. Let's explore these aspects further:

4.1 Selection of the Right Rootstock/Scion

Selecting the right rootstock and scion is a key factor for successful grafting. It's crucial to choose plants with the same stem size for a proper fit and compatibility. Moreover, grafting is ideally done when the plants have 2-3 true leaves, as this stage offers optimal conditions for success (Garner, 2013).

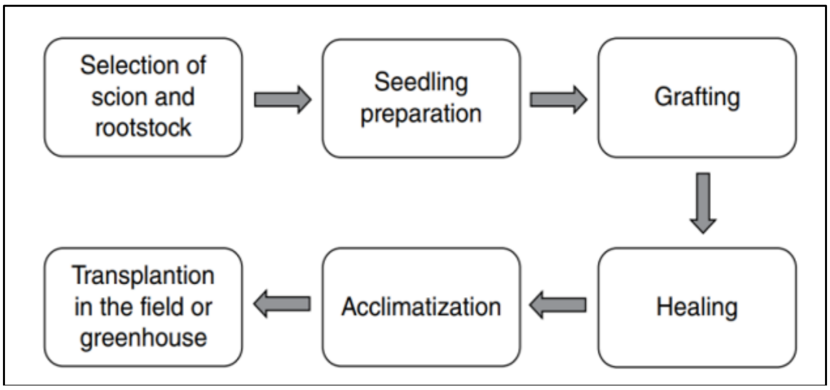

Fig. 1. Steps of grafting

4.2 Graft Compatibility

Graft compatibility is critical in ensuring the success of the grafting process. When the rootstock and scion are compatible, the mortality rate is significantly reduced, even in later growth stages. This compatibility encourages quick callus formation between the scion and rootstock. As a result, vascular bundles form, ensuring the grafted plant functions properly (Garner, 2013).

4.3 Grafting Aids

For effective grafting, certain tools are typically used. These include grafting clips, tubes, pins, and blades. These aids assist in securely joining the rootstock and scion, thereby providing stability and promoting the healing process.

4.4 Screening House

Prior to grafting, seedlings should be grown in a controlled environment, commonly a screening house. This structure should be built using a 60-mesh nylon net to keep out pests and diseases. The screening house also needs a double door, with the upper half covered by UV-resistant polyethylene material. This setup blocks harmful UV light, creating a suitable environment for seedling growth.

4.5 Healing of Grafts

The healing process is a crucial stage in vegetable grafting. It involves creating favourable conditions to encourage callus formation in grafted seedlings. In a healing chamber, maintain the temperature at approximately 28-29°C and a relative humidity of 95%. This should be done for 5-7 days in a partially shaded area, including 1-2 days of darkness (Bhoite et al., 2022). These conditions foster callus formation at the graft junction, leading to a more robust graft union. The primary goal at this stage is to establish a healing environment by regulating temperature, humidity, and light intensity.

4.6 Acclimatization of Grafted Plants

After the callus forms and the wounded surfaces heal, it's crucial to acclimatize the grafted plants to their new environment. This can be achieved by placing the plants under a mist system, in a greenhouse, or covering them with a clear plastic cover. These measures prevent leaf burn and wilting, ensuring the successful establishment of the grafted plants (Vince-Prue et al., 2014). By meticulously adhering to these critical prerequisites, the complex process of vegetable grafting can be executed successfully. This adherence is the key as it significantly influences the outcome, leading to the cultivation of improved plant varieties. These enhanced varieties possess a range of desirable traits, making them more beneficial for growers. Moreover, an added benefit of this successful grafting process is a noticeable enhancement in the productivity of these plants. Thus, it is clear that these prerequisites not only ensure a successful grafting process but also result in varieties with increased yield potential.

5. TECHNIQUES INCLUDED IN GRAFTING

Various grafting techniques are used according to the specific scions and rootstocks, grafting objectives, farmers' experience, and post-grafting management conditions. The survival rate of grafted plants depends on factors such as compatibility between scion and rootstock, quality and age of seedlings, quality of the joined section, and post-grafting management (Fallik et al., 2014). Initially, cleft grafting was the method used for melon, but its use declined significantly after the introduction of the tongue approach grafting method (Malik et al., 2021). This newer method became widespread in Asia due to its higher success rate and the uniform growth of grafted seedlings. In Spain, the one cotyledon method is used to graft a high proportion (over 90%) of watermelon plants (Malik et al., 2021).

5.1 Selection of Rootstock

In grafting, it is essential that the root system be more vigorous than the scion (Martínez-Ballesta et al., 2010). This robustness is critical as it enables the plant to overcome challenges associated with low soil moisture. This could be due to various environmental factors such as drought or poor irrigation systems. Moreover, the rootstock must possess the resilience to combat low fertility stress and salt stress. These stresses can emerge from a variety of sources including poor soil quality, over-fertilization (Nimbolkar et al., 2016). Furthermore, the root system should exhibit a high degree of hardiness. This means it should be capable of withstanding extreme weather conditions, whether it's the biting cold of winter or the scorching heat of summer.

Another important aspect to consider is the resistance of the root system to soil-borne pathogens, pests, and nematodes. This resistance is vital for the overall health and survival of the plant, as these factors can lead to various diseases and potentially result in the plant's demise if not properly managed. Lastly, the root system should enhance the plant's vigor and precocity. In other words, it should contribute to a more lively and robust growth and promote earlier maturity. This can lead to improved yield and quality of the plant, making it more beneficial for both commercial and personal growth purposes.

5.2 Choice of Scion

In order to be considered suitable, the scion must possess certain characteristics. Primarily, it should have the ability to produce fruits in larger quantities, thus ensuring a higher yield. Additionally, the quality of the fruit it produces should be superior, with a focus on factors such as taste, nutritional value, and overall appearance.

5.3 Cleft Grafting

This technique is often referred to as apical or wedge grafting. The process begins by carefully pruning the scion plants to maintain only 1-3 of the true leaves (Fig. 2). This ensures optimal conditions for the grafting to take place. The next step involves making an incision in the lower stem at a precise slanted angle. This cut is designed to form a tapered wedge, a crucial element for grafting. The scion, prepared with its tapered wedge, is then meticulously placed into a split that has been made in the rootstock. After the preparation of the scion plant, a small clip is used. The role of this clip is to maintain a firm contact between the scion and the rootstock. It's placed strategically to guarantee the proper interaction of these two components (Johnson et al., 2011). This method is most widely used in solanaceous crops.

5.4 Tongue / Approach Grafting

In this grafting method, rootstock and scion material of equal size is used. To achieve this uniform size, scion seeds are planted 5-7 days before rootstock seeds. Although this method requires more labour and space, it has a high seedling survival rate, making it popular among farmers and small nurseries. However, it isn't suitable for rootstocks with hollow hypocotyls. In the initial stage of the grafting process, small incisions or notches are carefully made on both the scion and the rootstock. These are the two primary components involved in the grafting process. Following the creation of these notches, they are aligned and fixed together using a clip. This clip acts as a stabilizer, holding the scion and rootstock together until they can fuse naturally. This is a critical step, as the alignment must be maintained for the graft to take successfully. Eventually, once the union between the scion and rootstock has healed and they have effectively become one plant, the final step is undertaken (Fig. 3). The scion is carefully separated from its original root system. This is to ensure that the newly grafted plant can grow independently, leveraging the strength and resilience of the rootstock.

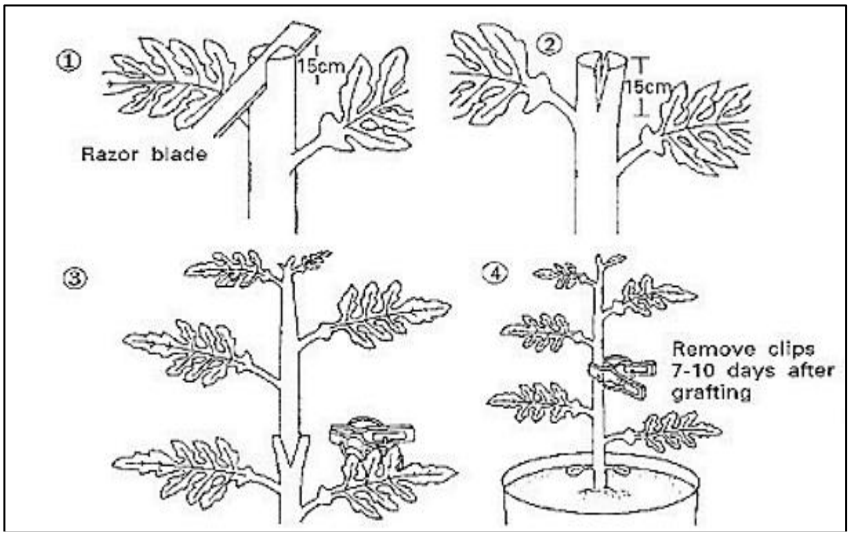

Fig. 2. Cleft grafting

5.5 Hole Insertion / Top Insertion Grafting

In the intricate process of grafting, the scion is carefully and precisely cut. This cutting is done in such a way that its vascular system is exposed. Concurrently, an insertion cavity is created in the rootstock. Once this cavity is prepared, the previously cut scion is then securely fixed into it. This fixation is typically done using a specialized clip, ensuring that the scion and rootstock are held tightly together. This secure attachment allows the vascular systems of both parts to successfully merge, enabling the grafted plant to grow as a single entity. This is the most popular method for grafting cucurbits where scion and rootstock with hollow hypocotyls are preferred. It's particularly favoured for grafting watermelon transplants because watermelon seedlings are typically smaller than the rootstock of bottle gourd or squash. This method requires an optimum temperature of 21-36˚C up until transplantation (Fig. 4). It's highly popular in China due to its strong union and superior vascular connection compared to the tongue grafting approach (Oda, 1999).

5.6 Splice Grafting/ Tube Grafting / One Cotyledon Splice Grafting

This technique is widely used and favoured by a large number of growers and commercial grafting transplant producers, offers a versatile approach to enhancing crop health and yield. It is adaptable across a broad range of vegetables, presenting the option to be implemented either manually or via mechanized equipment. This increases the method's accessibility and usage across different scales of farming. Particularly, this method has gained considerable popularity among growers of Cucurbit and Solanaceous vegetable crops. The versatility and effectiveness of this method make it an indispensable tool in modern agriculture (Fig. 5).

5.7 Mechanical Grafting

Grafting machines, or more aptly termed as grafting robots, are becoming an integral part of the grafting process. The inception of the first robotic 'one-cotyledon grafting system' traces back to the 1980s. It was pioneered in the land of the rising sun, Japan, by a visionary named Iam Brain. The system was primarily designed for cucurbit vegetables. The first prototype of this innovative system was brought to life in the year 1987 and underwent further modifications in 1989 (Ito, 1992; Kubota et al., 2008). One of the impressive features of this system is its swiftness—it takes a mere 4.5 seconds to complete a graft and boasts an impressive success rate of 95%.

The technologies that were incorporated into this revolutionary robot were not kept exclusive. They were shared with various agricultural machinery companies. This sharing of knowledge and technology stimulated the development of a prototype semi-automatic grafting system in Korea. The Rural Development Administration of Korea took a keen interest in the technology and developed several grafting robots. These were provided to plug seedling nursery growers at a price that was relatively lower than the market rates. By the turn of the millennium in 2001, Korea had successfully developed three different grafting robots. The Yopoong Company, a Korean enterprise, developed a simple and economical grafting machine. This machine was made available for local growers and has been exported to various Asian countries for over a decade. In addition, another semi-automatic grafting machine was developed by a private company in Korea and provided to growers. This semi-automatic multifunctional machine gained popularity and was adopted by many countries on account of its reasonable price, adjustability, and user-friendly handling.

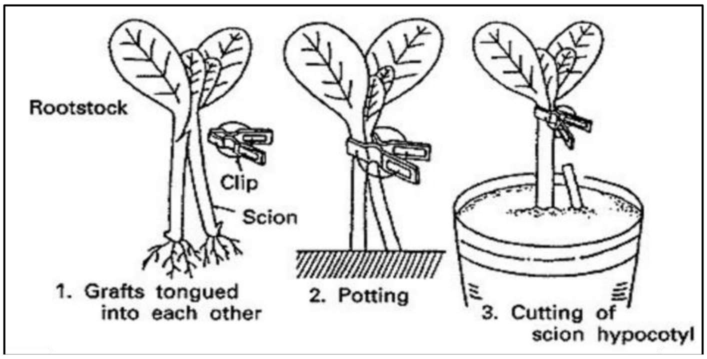

Fig. 3. Tongue / approach grafting

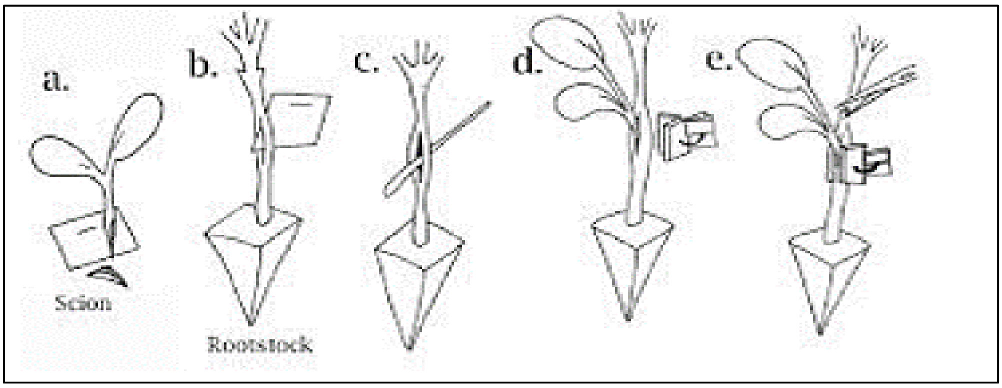

Fig. 4. Hole insertion / top insertion grafting

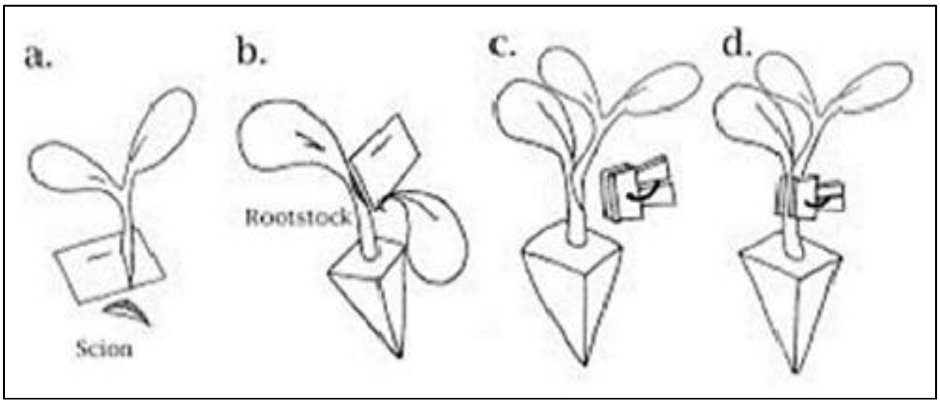

Fig. 5. One cotyledon splice grafting

In the Netherlands, the grafting technology took a leap with the development of a fully automatic grafting robot. This robot has a capacity of conducting 1000 grafts per hour and has been extensively used for tomatoes. In a similar endeavour, another fully automatic grafting robot was developed in Japan. This robot has a capacity of accomplishing 750 grafts per hour and a high success rate of 90%. As of today, a total of six models of semi- or fully automatic grafting robots are available in the global market. Three of these models have their roots in Japan, while one each originated from Korea, the Netherlands, and Spain. These machines are a testament to the advancements in grafting technology and the ongoing efforts to make the grafting process more efficient and economical.

5.8 Post-Graft Healing Environment

Ensuring the proper care of freshly grafted transplants is absolutely essential to guarantee a high success rate in the grafting process. The first two days post-grafting are particularly critical as water loss from the scion during this period can lead to wilting, jeopardizing the entire process and ultimately leading to failure. To mitigate this, maintaining a humidity level of 95% is not just recommended, but crucial. To foster the healing process, a proven strategy is to cover the grafted transplants with black plastic sheeting for a period of 5-7 days following the grafting. This measure not only enhances humidity levels but also reduces light intensity, creating an optimal environment for the graft to heal and grow. In addition, making use of plastic tunnels as makeshift healing chambers can be highly effective. By employing a healing room, commercial operations have been able to achieve an impressive 95% grafting success rate (Dong et al., 2015). It's also important to note that during the healing period, exposing the grafted plantlets to direct sunlight should be avoided at all costs. The success of a graft union is essentially founded on the relationship between the stock and the scion, assuming that all other factors such as grafting technique, timing, and temperature are satisfactory and well managed. Thus, providing the grafted transplants with the right conditions is key to ensuring a successful grafting process.

Table 1. List of company making grafting robot

Make	Country of origin	Distribution	Suitability	Characteristics
Helper Robotech (semi-automated machine)	Korea	Distributed to Asia, Europe and North America	Cucurbits and tomato	The first model that can graft both cucurbits and tomato. Widely marketed in Asia and North America. Produces 650-900 grafts h^{-1} at ≥95% success rate. Needs two to three workers to operate the machine.
Iseki (semi- automated machine)	Japan	Distributed to Asia and Europe	Cucurbits	Introduced to the Asian and European market. One machine has been introduced in the USA for trial use. Produces 900 grafts h^{-1} at ≥95% success rate. Needs two to three workers to operate the machine.
Iseki (semi- automated machine)	Japan	Distributed to Asia	Tomato and aubergine	Produces 800 grafts h^{-1} at ≥95% success rate. Seedling size required for grafting was too large for Japanese standard, limiting the market. However, the seedling size is acceptable for USA standard. Needs two to three workers to operate the machine.
Iseki (fully automated machine)	Japan	-----------	Cucurbits	Introduced in Japanese market in 2009. Produces 800 grafts h^{-1} at ≥95% success rate. A tomato model is also under development at IAM BRAIN". Only one person needed operate the machine.
ISO Group The (fully automated machine)	Netherlands	------------	Tomato and aubergine	Introduced in 2009. Produces 1000 grafts h^{-1}. A semi-automated model is also available that requires manual feeding of plants into the system.
Conic System (semi-automated machine)	Spain	------------	Tomato	A semi-automated robot to cut tomato scions and rootstocks at a selected angle. Produces 400-600 grafts h^{-1}. Only one person needed to operate the machine.

6. PROBLEM ASSOCIATED WITH VEGETABLE GRAFTING

The production and management of grafted transplants are accompanied by various challenges. One of the main hurdles is the labor-intensive nature of the technique, which requires specialized trained workers. These workers need to possess the necessary skills and expertise to perform grafting effectively. Additionally, time management plays a crucial role in the process, as it involves the careful scheduling of activities such as sowing the rootstock and scion seeds. Creating an optimal environment for graft healing is another important aspect of grafted transplant production. This controlled environment is necessary to ensure successful graft union and promote healthy growth. Moreover, the use of efficient grafting machines and robots can significantly streamline the process, increasing productivity and reducing costs. However, even with proper management and technique, challenges can still arise. Overgrowth of transplants under field conditions is one such challenge that may occur. This overgrowth can negatively affect the yield and quality of the scion fruit, leading to potential economic losses. Furthermore, rootstock-scion incompatibility may manifest during the initial stages or even after transplantation in the field, further complicating the process. To overcome these challenges, careful selection of rootstock and scion combinations is essential. The prevailing soil and environmental conditions of the specific area must be taken into consideration when making these selections. This ensures compatibility and enhances the chances of successful grafting.

Another consideration is the cost associated with obtaining the necessary rootstock and scion seeds. Hybrid and special types of seeds can be more expensive, adding to the overall production costs. Therefore, careful planning and budgeting are needed to optimize resource allocation. During the healing process or after transplanting, the development of rootstock suckers or offshoots needs to be addressed. These growths can interfere with the graft union and overall plant development. Regular removal of these suckers is crucial to maintain the health and vitality of the grafted transplants. Additionally, grafting introduces the risk of pathogen spread, particularly for seedborne pathogens. Examples of such pathogens include bacterial canker in tomatoes caused by *Clavibacter michiganensis* sub sp*. michiganensis*, bacterial fruit blotch in watermelon and melon caused by *Acidovorax citrulli*, charcoal rot in melon and bottle gourd caused by *Macrophomina phaseolina*, and viral infections such as tomato mosaic virus and pepino mosaic virus in tomatoes. The use of two seeds in the grafting process, as well as the use of cutting instruments, can contribute to the potential spread of these pathogens. To mitigate this risk, it is crucial to implement proper procedures in the nursery. This includes using seeds that have been certified as free of pathogens, ensuring regular disinfection of cutting instruments, and promoting hygienic practices among grafting workers. Clean clothing and disinfected hands should be maintained to prevent contamination. Furthermore, periodic disinfection of grafting areas and plant growing environments is necessary to minimize the risk of pathogen transmission. Continuous monitoring of the phytosanitary status of seedlings is also essential to detect and address any potential issues promptly.

7. CONCLUSION

In conclusion, commercial vegetable grafting continues to grow in importance, offering significant advantages in crop yield, disease resistance, and stress tolerance under adverse environmental conditions. As demand for grafted vegetables rises, future research should focus on advancing grafting technologies, improving nursery management, and addressing labor challenges through automation, such as grafting robots. Additionally, the development of advanced nurseries, seed-priming techniques, and storage technologies can further enhance the success of grafted transplants. Digital tools, such as crop models and management software, will play a crucial role in optimizing grafting practices, providing valuable insights for growers. Despite challenges in production, the continuous innovation in grafting techniques ensures that this practice will remain a cornerstone of sustainable agricultural practices globally, supporting increased productivity and resilience in the face of climate change and other environmental pressures.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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