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Grafting technique a novel advancement in vegetable breeding

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Abstract
Vegetable grafting is a tool for the development of a distinct plant source that aids in the dramatic drop of plant vulnerability to biotic and abiotic stress, and the reduction of production costs by minimizing plant protection chemicals. Japan and Korea were the pioneers of vegetable grafting; today, this practice plays a unique role in maximizing production per unit area around the world. Grafting is mostly done in vegetable and fruit crops for controlling Soil-borne diseases *viz*., Fusarium wilt, Bacterial wilt, quality enhancements such as TSS, pigments, and overcoming graft incompatibility through bridge crossing (inter-stock). Grafting is an art that requires specialized training. Robotic grafting has recently entered the market in order to reduce labour costs and optimize costs. The current review meticulously gathered information on rootstocks, scions, and interstocks. Graft compatibility and incompatibility in relation to physiological, biochemical, and molecular factors supporting graft success.

Keywords: Grafting, robotic grafting and graft compatibility

Introduction
India is the world's second-largest producer of vegetable crops, after China. Area under vegetable production was 10.35 million hectare and production 191.76 million tonnes. In India Potato ranks first in area (2.15 mil ha) and production (51.30 mill t) fallowed by Onion and Tomato (NHB data, 2019-20, second advance estimation) [54]. India has a diverse range of land types and climates, which are reflected in the evolution of various soils and plants. There is also a strong link between soils, landforms, climate and plants (Maurya *et al*., 2020) [48]. The focus of the researchers is currently on increasing the quality of horticulture products. Vegetables are a great source of complex carbohydrates, along with vitamins, minerals, phytochemicals, and nutraceuticals. Promotes their physical and mental well-being and helps them avoid lifetime disorders. Many dieticians support to take 300g of vegetables every day to take our balanced diet along with other diets. There are 125 g of leafy vegetables and 75 g of other veggies 100g root and tuber vegetables (New Delhi: ICMR).The major groups of vegetable crops grown in India are solanaceous and cucurbits. It's becoming more popular for its salad, pickling, and processing industries. For farmers, the majority of these crops are low-value, high-income crops. The key limitations for quality of horticulture crops produce are abiotic and biotic stress (Arzani. 2008) [8]. From the beginning (at the nursery level) of the production process to commercialization, soil-borne diseases cause significant losses in vegetable crops (Garibaldi *et al*., 2009) [22]. Unfavourable soil and environmental conditions, such as drought, excessive temperature, salinity, flooding, low nutrients, organic and heavy metal contamination, as well as biotic restrictions such as soil and air-borne pests and diseases, are limiting vegetable output around the world (Alfocea *et al*., 2014) [60]. (Hong *et al*., 1710) Vegetable grafting is a centuries-old method of producing large gourds for storing rice. In summary, grafting is being employed in a variety of ways for commercial, sociological and environmental reasons, as well as to further our understanding of fundamental plant science processes. In Chinese, Korean, and Japanese old records on vegetable grafting documented and conserved. Vegetable grafting has only become a commercially viable option after 1950s (Lee *et al*., 2010; Lee and Oda, 2003; Chang *et al*., 2008; Buller *et al*., 2013) [36]. Early twentieth century the use of appropriate rootstocks has long been known to reduce the issues related with successive cropping and stress tolerance (Bie *et al*., 2017; Maurya *et al*., 2019; Dash *et al*., 2021) [47].

Commercial vegetable grafting, on the other hand, began in the early twentieth century with the goal of controlling soil-borne diseases (Louws *et al*., 2010).Both the public and private sectors now conduct full-fledged research projects. Vegetable grafting has resulted in yield increases of up to 80% in the Solanaceae family and 60-90 percent in the Cucurbit family (Dash *et al*., 2021).

Historical Background

Grafting is prevalent in nature, and it's likely that seeing natural grafts led people to employ this technique in horticulture ancient time (Mudge *et al*., 2009) [51]. Melnyk and Meyerowitz (2015) [49], several references to fruit grafting can be written in the Bible, as well as ancient Greek and Chinese writings, suggesting that grafting was used throughout Europe, the Middle East, and Asia by the 5th century. In the late 1920s, Japan and Korea pioneered scientific vegetable grafting by grafting watermelon onto gourd rootstocks to avoid soilborne infections (Ashita, 1927; Yamakawa, 1983) [9, 80]. Agricultural extension staff in Japan and Korea popularized this technological innovation to farmers. In the early 1930s, Japan pioneered the commercial purpose of grafted transplants by grafting watermelon onto bottle gourd. In the 1950s, aubergine (*Solanum melongena* L.) was initially grafted on to scarlet aubergine (*Solanum integrifolium* L.) among the Solanaceous crops (Oda, 1999) [59]. In the 1960s, tomato grafting (*Solanum lycopersicum* L.) became popular (Lee and Oda, 2003) [38].

Dr. R. M. Bhatt and his team started first vegetable grafting work in India in the year 2013 at IIHR, Bangalore, to find the best rootstocks for waterlogged conditions. Cucurbit grafting in *Momordica cochinchinensis* was studied at the NBPGR regional station in Thrissur, Kerala, in order to enhance the productivity by grafting female plants onto male plants. Dr. Pradeep Kumar, CSKHPKV, Palampur, started working on grafting and identified best rootstock in brinjal, chilli, tomato, Potato and cucurbit rootstocks for importing bacterial wilt and nematodes resistance. Grafting is also done by some private players. VNR Seed Private Limited in Chhattisgarh is one of them, supplying farmers with grafted brinjal seedlings resistant to bacterial wilt and many great results have come from the company's blue ocean approach, such as the introduction of grafted vegetables and root stock seed..'Takii seed India private limited' is the other seed company working on vegetable grafting in India (Kumar *et al*., 2015) [33].

Indian history about mechanized grafting (Robotic technology)

In India two major Public institutions like CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur and department of horticulture in Tamil Nadu Agricultural University (TNAU) having mordernized vegetable grafting system with use of robotic machines (Automated grafting machine). This allows for the production of up to 800 grafted seedlings every hour. The machine was imported from Korea by TNAU, So far, they have produced around 50,000 grafted plants using mechanical grafting. Similarly, Prof. A.K. Sarial dedicates a robotic vegetable grafting system to the farmers of Himachal Pradesh: CSK H.P. Agriculture University.

Grafting machines or robots are becoming more popular. In the 1980s, Japan-based Company 'I am Brain' manufactured the first robotic grafting machine (one-cotyledon grafting system) specifically for cucurbits.In the 1980s, after many years of research, the Netherlands and Japan developed fully automated robotic grafting machines capable of 1000 and 750 grafts per hour, respectively. Korea, Japan, the Netherlands, and Spine are the world leaders in the production of grafting machines. Different countries have different grafting robot features (http://cals.arizona.edu/grafting/grafting-robots).

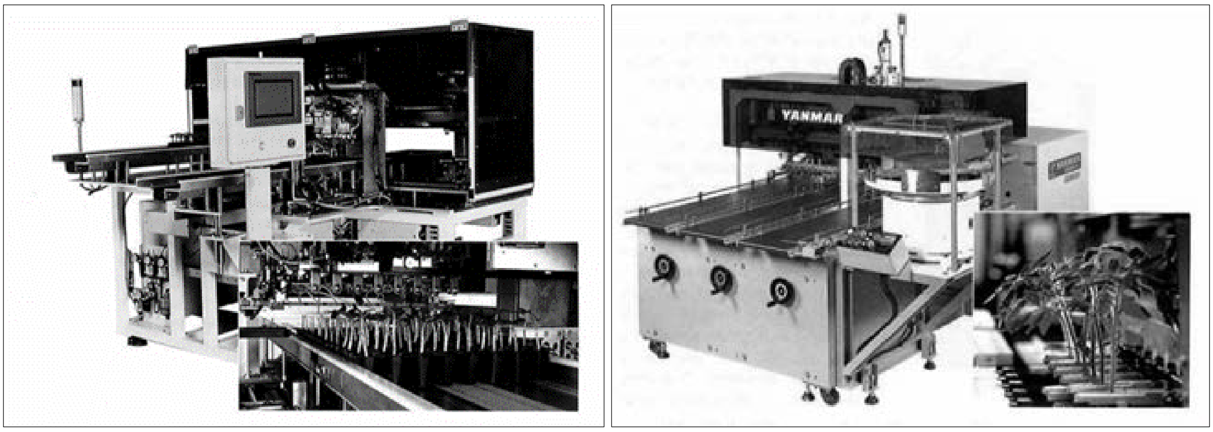

Fig 1: Fully automatic grafting (Suzuki *et al*., 1998) [74].

Vegetable grafting and types

Grafting is the art of connecting scion and rootstock of different plant species and growing as a single plant, that union of scion and root stock is called matrix, (Janick, 1986) [51].

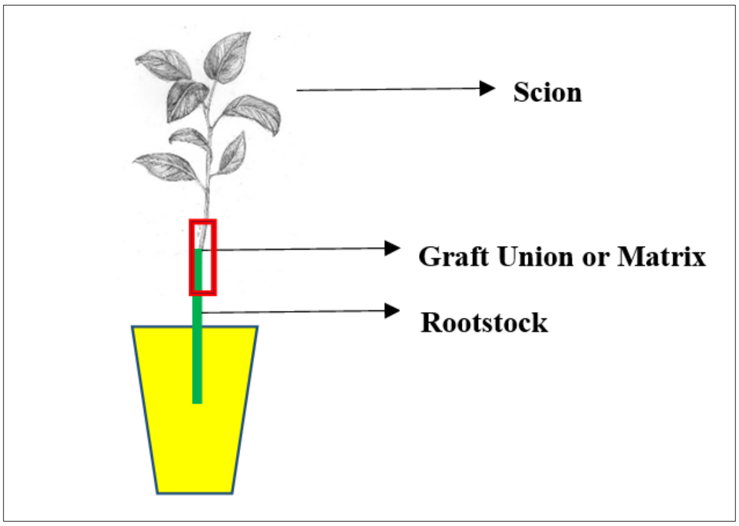

Fig 2: Schematic representation of grafted plant.

The grafting method chosen is determined by:
1. The crop's nature,
2. The farmers' experience
3. Personal preference.
4. The number of grafts required
5. The aim of grafting
6. Labour and machine availability
7. Facilities for infrastructure

Hand grafting, in the perspective of farmers and nursery units, is superior to robotic grafting, which has a higher grafting suc cess rate. (Lee *et al.*, 2010) [36, 37, 39].

Types of Vegetable grafting:

1. Hole insertion: This has been the most common method for cucurbits. Small hypocotyls on the scion and rootstock are preferable in this procedure. Hole insertion grafting is recommended for grafted watermelon transplant production because watermelon seedlings are small when compared to rootstock (bottle gourd or squash). For this method rootstock should be selected 7-8 days (Bottle gourd) and 3-4 days (Squash) old. Rootstock seeds are sown 5–10 days before scion seeds are sown, and grafting is done 20–25 days after scion seeds are sown in the case of tomato and aubergine (Lee *et al.*, 2010) [36, 37, 39]. Both rootstock and scion seedlings should be homogeneous, robust, and strong at the time of grafting. Graft union healing needs 21-36˚c. Compared to tongue grafting, this method results robust union and vascular linkage (Oda, 1994).

2. Cleft grafting: Apical or wedge grafting is another term for it. The lower stem of the scion plant is cut to a slant angle to produce a tapered wedge, and a clip is applied to make contact between the scion and the rootstock after placing the scion into the split made (Johnson *et al.*, 2011) [30]. Solanaceous crops are the most commonly used crops for this strategy.

3. Tube or Japanese grafting: When seedlings are grown in plug trays, this is the most common method. It's a more convenient and time-saving form of vegetable grafting than traditional grafting. Seedlings of small size can be accommodated in a healing room or an acclimation chamber. In rootstock, a 45^0 incision below the cotyledon yields. In scion, a similar cut is also available. The rootstock and scion are joined using a tube, and the tray is placed in a healing chamber for up to 7 days.

4. Tongue approach grafting: It is a more time-consuming procedure that requires more space, but it has a higher success rate than other ways. Small farmers and nurseries are more likely to use it. As rootstocks, seedlings with hallow hypocotyls are not employed. Both the scion and the stock are of equal size. One week before rootstock raising, scion seeds are sown to ensure consistent scion size. Cucumber and pumpkin seeds are planted 10-13 days and 7-10 days before rootstock seeding, respectively. To prevent the shoot from growing any further, the rootstock shoot tip is removed. Both the scion and the stock have a tongue-like incision, and the graft union is done with the help of a plastic clip at the graft union point.

5. Slant-Cut Grafting: This is a widely used and popular robotic grafting technique that was developed.

6. Pin grafting: Splice grafting and pin grafting are both methods of grafting. To hold the grafted position, specifically engineered pins are utilized in fitting clips.

Recent Innovations in vegetable grafting

There have been numerous new innovations produced to accomplish grafting in vegetables recently, and a few of them are detailed below:

Double grafted and single grafted tomato: A tomato is a plant that has been grafted from a vegetable. Cleft grafting was used to graft tomato scions onto potato rootstocks. Over 500 cherry tomatoes with a TSS of 100 degree Brix were harvested above ground. Indigo Rose, Brandywine, and Sun Sugar are single tomato grafts. In 2010, Log House established in the United States the process of growing double grafted tomato plants with red and yellow pear tomato scions utilising Big Beef or Geronimo rootstock.

Micro-grafting: To eradicate viruses from infected plants, *in vitro* grafting using very small or micro explants ($1/1000^{th}$ mm^3) from meristematic tissues is used. In herbaceous plants, micro grafting has been used to investigate the physiology of grafting and the chemical basis of cell-to-cell interactions. Although pricey, this approach allows for the rapid propagation of virus-free plants.

Table 1: Grafting methods and rootstocks used in vegetable crops:

Scion plant	Rootstocks	Methods
Eggplant	*Solanum torvum S. sissymbrifolium Solanum khasianum*	Tongue and cleft method. Cleft method Both tongue and cleft methods
Tomato	L. *pimpinellifolium S. nigrum*	Only Cleft method Tongue and cleft methods
Cucumber	*C. moschata Cucurbita maxima*	Hole insertion and tongue method tongue method
Water melon	*Benincasahispida C. moschata C. melo C. moschata × C. maxima Lagenariasiceraria*	Hole insertion and cleft method Hole insertion and cleft method Cleft method Hole insertion method Splice Grafting
Bitter gourd	*C. moschata,Lagenariasiceraria*	Hole insertion and tongue method Hole insertion

Scion, Root stock and Interstock: In this study, we define a successful graft as one in which the scion and rootstock establish a graft union. Transplants between closely related species have long been thought to be more successful than grafts between distantly related species.Hatton published one of the first general assessments on rootstock/scion relationships in 1930 [26]. The rootstock is a water and mineral absorber that is situated below ground. The scion is the aboveground section of the plant that is responsible for carbon dioxide assimilation, water storage, glucose accumulation, and plant growth hormones through its leaves. When the scion and rootstock are distantly related, interstocks, or intermediate stem pieces, have been used for exuberance, dwarfing, and adding compatibility between the two.

Qualities of graft scion and rootstock: The suitable rootstock and scion cultivars must be chosen for grafted vegetable production to be successful based on the parameters such as genetic purity, survivability, productivity, fruitfulness, and meeting consumer expectations are basic needs of the better scion. A deeper root system (drought tolerance), good nutrient uptake potential, disease resistance,nematode tolerance, compatibility with the scion cultivar, and wider adaptability in allenvironmental conditions are all factors considered when choosing rootstock cultivars.

Reasons for graft incompatibility: Degree of graft success depends on primary isolating layer formed between stock and scion (Thiel. 1954) [75]. De Stigter, 1956 [17]. In cucurbitaceous crops graft success depends on genetic potential, compatible size, number of stock leaves, photosynthesis, and principle actions of sieve tubes between graft partners. Length of the intermediate stem (1.5 mm) actively works when melon stem used in between cucumber (Scion) and *Cucurbitaficifolia* L.(Rootstock). The larger the taxonomic gap between stock and scion, the less likely a good graft union would happen. This indicates that intraclonal>interclonal> intraspecific> interspecific >intrageneric> intergeneric>intrafamilial is the theoretical success of a certain graft union combination (Dogra *et al.*, 2018).Three primary processes normally occur during the development of a compatible graft: rootstock and scion adhesion, callus cell proliferation at the graftvascular interface or callus bridgedifferentiation at the graft-to-host contact.improved success 1.5 cm deep (a "depth cut"), around 75% of the depth of the stem Scions were clipped to 1-3 leaves, and the lower stem was cut into a tapered wedge to fit inside the rootstock's depth cut.

Table 2: Basic inputs for vegetable grafting

Wrap	Dimensions	Crops	Price (c/m)
Grafting tape	1.9 cm × 55m	Vegetable crops	12.3
Masking tape	1.9 cm × 55m	Vegetable crops	1.7
Electrical	1.9 cm × 18m	Vegetable crops	4.2
Duct tape	5.0 cm × 55m	Fruit crops	5.4
Polyethylene strip	3cm x 100 m	Vegetables crops	198 /- (complete role)
Grafting clips			
Type of clips	**No. of clips per pack**	**Crops**	**Price**
Spring loaded tomato plant grafting clip, 4 to 6mm	25Pcs	Tomato, Cucumber,	600/-
Durable Transparent Grafting Clips	100Pcs	Cucurbits	199/-
Silicon tube grafting clip (2.5mm)	50 Pcs	Tomato, Cucumber, Bottle Gourd, Capsicum	299/-


Spring loaded tomato plant grafting clip, 4 to 6mm


Silicon tube grafting clip (2.5mm


Durable Transparent Grafting Clips


Polythene grafting tape

Physiology of graft success: Plasmodesmata are complex, dynamic structures that provide a unique avenue for symplastic cell communication and could be used to connect cells in the graft bridge.One theory is that rootstock-induced vigour is caused by signals like as water, nutrients, and, in particular, hormones and nucleic acids that travel through the graft union and influence scion growth. A large number of mobile macromolecules can flow through the vascular system, and more than 800 tiny organic compounds from various biochemical groups have been discovered in the xylem sap of grafted tomato seedlings (Albacete *et al*., 2014) [2]. A favourable temperature and humidity level in the growing chamber aid in the development of callus between rootstock and scion.Temperature influences callus occurrence in vegetable crops. Hartmann and colleagues (1997) [25] the ideal temperature for callus production is 26 °C (Erdogan 2006), and no callus formation occurs during healing below 20 °C (Wilbur *et al*. 1998) [78]. Cleft grafting is ideal for most of the crops, with 1.5 cm deep (a "depth cut") rootstock and 1-3 leaves stage of the scion (Petran*et al*., 2014) [63]. The rootstock genotype or rootstock–scion interactions regulate mineral element uptake and transport in vegetables.P concentrations in the leaves of grafted watermelon and melons more increases and helps in the transportation of nutrients. $Ca2^{+}$ concentrations were lower and higher $Mg2^{+}$ in watermelon plants grafted onto *Cucurbita maxima*, Lu*et al*., (2020).

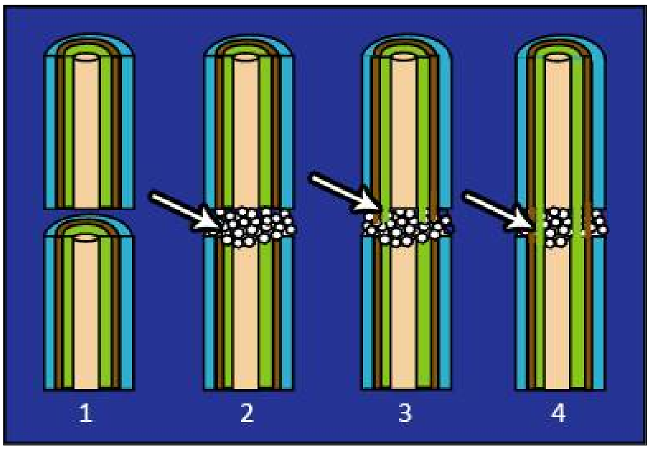

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Fig 3: The steps of graft union creation are depicted in the cartoon to the right:

1. The alignment of the scion's vascular cambium and the rootstock's vascular cambium, as well as the wound healing response. Between the scion and the rootstock,
2. A callus bridge forms.
3. New xylem and phloem formation.
4. The vascular link between the scion and the rootstock has been completed.

Hormonal, molecular and biochemical impacts on graft success:

The scion–rootstock relationship is important in controlling basipetal (Downward via the phloem from scion to rootstock) and acropetal (upward from the rootstock to the scion via the xylem) transport. Phytohormones (ABA, IAA, and CK) may act as long-distance signals in grafted plants, according to these findings. Jasmonic acid polar movement (Roots to scion) and red light sensed scions of the grafted tomato promotes the production of IAA (Guo*et al*., 2016) [24]. The formation of scion-rootstock interactions is dependent on proper hormonal balance. Auxin, cytokinins, ABA, and ethylene all play key roles in the development of grafted plants. Hormonal signalling considerations may aid in the breeding of superior rootstocks. According to the "hormone message concept," hormones are produced in one region of the plant and affect another. Disruption of the any graft will give incompatible Sign after 25 days. Following the development of the grafting connections, there is a hormonal imbalance in the root system, predominantly of auxin and ethylene. Incompatible graft roots and scions contain more IAA than compatible graft roots and scions. Exogenous administration of the auxin transport inhibitor, 2,3,5-triiodobenzoic acid, to the stem of grafted transplants aids in the blockage of basipetal IAA transport and supports success of the incompatible grafts (Aloni*et al*., 2010) [4]. Albacete *et al*. (2008) found a high association between leaf xylem trans-zeatin content, indole-3-acetic acid, and ABA in commercial cultivars grafted on hybrid root stocks of *S. lycopersicum L.* × *S. cheesmaniae L.* Riley grown in salt stress environment.At 3 DAG, large-diameter structures (3–8 µm) characterised as'microtubules' were discovered in artichoke–cardoon grafts, supporting water, nutrients, and molecular signalling (Trinchera *et al*., 2013) [76]. The *iaaM* (gene for auxin synthesis) gene in wild tobacco scion and the *CKK* (cytokinin degradation gene) gene in transgenic tobacco rootstock demonstrate no lateral branching in the success graft (Camalle *et al*., 2021) [13]. Phytohormones (ABA, IAA, and CK) act as long-distance signals in grafted plants, jasmonic acid polar movement (Roots to scion) and red light sensed scions of the grafted tomato propromote production of IAA (Guo *et al*., 2016) [24]. Light is a unique abiotic factor involved in the lateral transport of hormones (auxins) within the plant body, when cucurbita rootstocks are under salt stress, by eliminating Na^{+} from leaf mesophyll cells and retaining K^{+} in leaf mesophyll cells with early closure of ABA-induced stomata (Niu *et al*., 2018b) [56].

A number of regulatory mechanisms that influence plant cell proliferation in growth zones and organ size *AINTEGUMENTA-like* (AIL) transcription factors (TFs) are key regulators in the developmental processes of graft union (Horstman *et al*., 2014) [27]. Shoot phyllotaxy is controlled by *AIL5/PLT5*, *AIL6/PLT3*, and *AIL7/PLT7* genes which promote auxin production in the shoot apical meristem (Prasad *et al*.,

2011) [32]. Dynamic gene/protein expression profiles in the oriental melon transcriptome and proteome during fruit development (*Cucumismelo L. var. makuwa*). Transcription factor-encoded genes, including as *AP2/ERF*, *C2H2*, *MYB*, *bHLH*, and *AUX/IAA*, were substantially more robustly expressed in the grafted plants. These genes are quite well actors in the regulation of cognitive stages and hormone transmission metabolism (Chen *et al.*, 2021) [14]. Genomics, transcriptomics, proteomics and metabolomics place major role vegetable grafting while screening the better root stocks for abiotic and biotic stress breeding. The mechanisms of transcription, gene expression, and protei n translation, as well as the flow of material between rootstoc ks and scions, can not only govern growth but also increase th e adaptability of vegetables to their surroundings.Watermelon and bottle gourd heterograft's clarify distinct molecular processes, with bottle gourd rootstock increasing the size and rind thickness of watermelon fruits. Watermelon and bottle gourd grafting are dependent on sugar enzyme activity, and the *TOR* inhibitor *AZD-8055* inhibited graft union formation with a lower energy charge, whereas xylem reconnection and grafted plant development were boosted when *AZD-8055* was combined with exogenous glucose (Miao *et al.*, 2021).

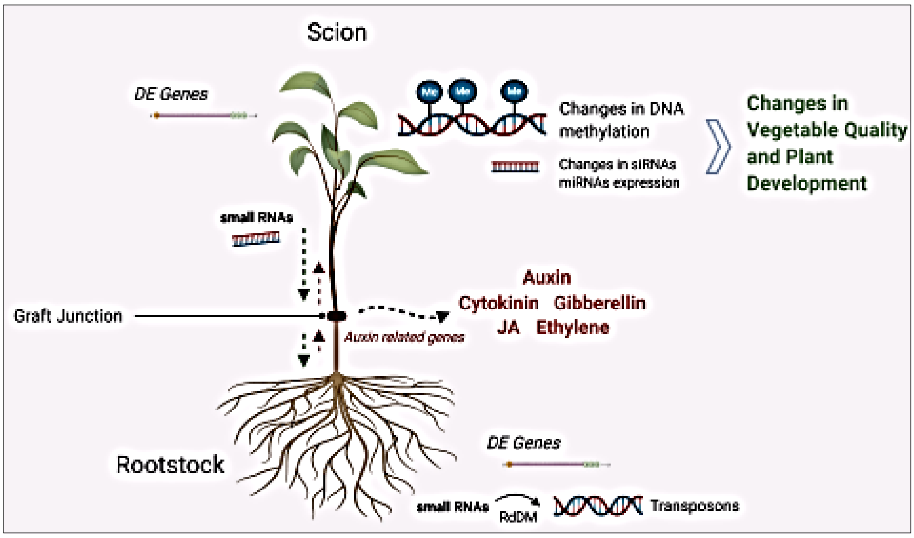

Fig 4: Molecular mechanisms taking place in grafted plants, quality breeding. (Tsaballa *et al.*, 2020).

Vegetable grafting enhance horticultural (Quality) traits:
The quality of horticultural produce ultimately captures the expectations to be met. External appearance, shelf life, and nutrient status of the horticultural commodity all influence market price (Schreiner *et al.*, 2013) [70]. Many researchers used grafting as a power full tool to enhance palatability traits.

Family Cucurbitaceae, Watermelon, melons and cucumber
For fruit weight improvement *Cucurbita maxima* × *C. moschata* and gourd (*Lagenariasiceraria*) rootstocks and watermelon as a scion. Interspecific Cucurbita species and Bottle gourd, When used as rootstock for small-fruited watermelon scions, bottle gourd rootstocks can significantly increase yields (number of fruit per plant increases) and large-fruited scions usually translate into a tendency for higher unit fruit weight (Proietti *et al.*, 2008) [64]. Watermlon sweetness enhances*C. lanatus var. citroides* (Fredes *et al.*, 2017) [19] and is decreased by *C. argyrosperma* and *C. pepo* (Davis and Perkins-Veazie, 2005). *C. maxima and C. moschata* rootstocks have been shown to substantially boost lycopene and aroma levels in watermelon fruit, (Fredes *et al.*, 2017 and Soteriou *et al.*, 2014) [19, 73]. Melon hybrid 'AS10' cases of rootstock influences increase SSC, *C. maxima*, and *C. moschata* have been used as a good source of rootstocks, and are now the most popular trade rootstocks for cucumber (Lee *et al.*, 2010) [36, 37, 39].

Family Solanaceae, Tomato, Pepper and Eggplant
There are interspecific hybrids rootstock such as *S. lycopersicum* and *Solanum habrochaites*, as well as rootstocks from other species, such as *Solanum torvum* L. or *Solanum melongena* L. As a result, growers frequently follow the advice of breeders in Tomato. Salt tolerant goji berry (*Lycium chinense* Mill.) used as rootstock for for reducing fruit size as like cherry tomato (Huang *et al.*, 2015) [28]. Blossom end-rot (BER) incidence reduced when grafted on (*S. habrochaites*) rootstocks 'Brigeor,' 'Maxifort,' and LA1777 (Ntatsi *et al.*, 2014) [57]. Ca content was increased by grafting still not clear the molecular aspects behind it (Savvas, *et al.*, 2017) [68, 69]. Cv. Black Beauty as a scion on root stock of *S. torvum*, *S. incanum* × *S. melongena* and *S. melongena* × *S. aethiopicum* improves the fruit weight (Gisbert *et al*.,2011b) [23], increased total phenolics and total polyphenols when 'Cristal' cv and Sicilian landraces grafted on rootstocks of *S. macrocarpon* and *S. torvum*, Sabatino*et al*. (2016) [67]. Choice of the rootstock greatly influence on the vitamin C content, lycopene and beta carotene content when grafting in pepper (Gisber *et al.*, 2010).

Type of rootstock	Rootstock cv.	Scion	Major beneficial characteristics	References
C. melo subsp. Agrestis Pat 81 x *C. melo subsp. Melo*.Piel de sapo	F_1Pat81	Local snake melon (*flexuosus*) cv.	Variable level of resistance to fungal stresses (*Neocosmosporakeratoplastica*and *N. falciformis*)	Flores León *et al.*, 2021 [83]
Cucurbita RS	Kardosa and Nun 9075	*Cucumis melo*c ultivars (Citirex and Altinbas)	Citirex/Nun9075 and Citirex/Kardosa graft combinations has higher salt tolerance	Ulaset *al.*, 2020 [93]

Cucurbita maxima x *C. moschata*	(Interspecific Cucurbita RS)	Citirex F_1, ManisaAltinbas	Improve performance under salt stress	Ulas *et al.*, 2019 [77]
Cucumisficifolius x C. anguria *C. ficifolius x C. myriocarpus*	UPV-FA(Fian) UPV-Fmy (Fimy)	Muskmelon and Pie de Sapo	Resistant to *F. oxysporum f. sp. melonis* race 1.2 Mild to moderate resistant to root knot nematode High graft success rate (>90%)	Caceres *et al.*, 2017 [82]
Cucumispustulatus (PI 532673)	-	Melon, Cucumber, Watermelon	High resistance to both Fusarium wilt and root knot nematode. Good compatibility Improved plant growth and increased yield High graft success rate (>90%)	Liu *et al.*, 2015 [43, 90]
USVL482-PMR and USVL351-PMR (Bottle gourd)	-	Mickey Lee (watermelon)	Incomplete resistance wasn't imparted on the scion	Kousik, 2018 [87]
Citrulluslanatus var. citroides	RKN resistant rootstock lines	Tri-X-313 (watermelon)	High degree of RKN resistance with heaviest fruit yield and greatest numbers of fruit	Thies*et.al.*, 2015 [92]

Table 3: Grafting in major vegetable crops.

Crop name	Scion	Root stock	Features	Reference
Watermelon	watermelon	(*Cucurbita maxima* (Duchesne) × *C. moschata*(Duchesne ex Poir)	Quality fruit	Kyriacao*et al.* (2017) [34]
Bottle gourd	Bottle gourd	*Lagenariasiceraria*	Quality fruit	Kyriacao*et al.* (2017) [34]
Tomato	*cv.* Big Dena	'Maxifort	Increase in range of yield under favourable saline conditions	Semiz and Suarez (2015) [71]
Tomato	RVTC 20, 0224-53 and RVTC 57, S. habrochaites	Physalis and Cocona	Good compatibility	Zeist *et a*l., (2017) [81]
Tomato	'Siriana' and 'Buzau 1600	'Emperador' and 'Groundforce'	Highest yield, more dry matter,	Doltu*et al.*, (2019)
Brinjal	Brinjal	'Beaufort'	Fruit quality and yield, resistance to *Verticillium* wilt	Marsiae*et al.*, 2014, Johnson *et al.*, (2014) [31] & Miles *et al.*, (2015) [50]

Table 4a: Biotic stress tolerance

Scion	Rootstock	Purpose	Reference
Melon	*C. melovarflexuosus, varconomon, varagrestis*, Asian landraces	Tolerance to nematodes Tolerance to *Monosphorascus*vine decline *Fusarium* wilt tolerance	Ito *et al.*, 2014 Jang *et al.*, 2014 [85] Lee and Oda, 1993
Melon, Watermelon, Cucumber	*Cucumis maxima* × *Cucumismoschata*	*Fusarium* wilt tolerance and fruit quality Management of *Verticillium* Tolerance to nematodes Higher yield, larger fruit	Zhou *et al.*, 2014; Buller *et al.*, 2013 Goreta Ban *et al.*, 2014 Zhang *et al.*, 2014
Cucumber	*C. moschata*	Tolerance to *Fusarium* wilt	Traka-Mavrona*et al.*, 2000
Watermelon	*Lagenariasiceraria*	Improved tolerance to *Phytophthoracapsici* Tolerance to powdery mildew	Kousik*et al.*, 2012 [88] Kousik*et al.*, 2018 [89]
Watermelon, Melon	*Citrulluslanatus var. citroides*	Tolerance to *Fusarium* wilt Tolerance to nematodes	Keinath and Hassell, 2014 [86] Thies*et al.*, 2015 [92]
Cucumber, Melon	*Benincasahispida*	Tolerance to *Fusarium* wilt Tolerance to *Verticillium* wilt	Trionfetti Nisini *et al.*, 2002 [91] Galatti *et al.*, 2013 [84]

Table 5: Abiotic stress tolerance:

Crop name	Scion	Root srtock	Features	Reference
Tomato	Faridah *cv*	Unifort *cv*	Increased uptake of Ca^{+2} and K^{+} and Salinity tolerant	Al-Harbi*et al.*, (2017) [3]
Tomato	Tomato	*Solanum lycopersicum L.* × *Solanum cheesmaniae*	Salt stresstolerence	Albacete *et al.* (2010) [1]
Tomato	ArkaRakshak and ArkaSamrat	IC-111056 IC-354557	Flood tolerant	Bahadur *et al.* (2015)
Tomato	Tomato	Beaufort" (*S. lycopersicum* L. × *S. habrochaites*	Drought tolerence	Altunlu and Gul (2012) [5]
Tomato	Ikram	Maxifort	Heavy metal toxicity	Kumar *et al.*, (2015) [33]
Tomato	cv. Primadonna	He-man and Maxifort	Greater nutrient and water uptake and abiotic stress tolerant	Savvas*et al.*, (2017) [68, 69]
Tomato	cv. Big Dena	Maxifort	Saline conditionstolerant	Semiz and Suarez (2015)

				[71]
Tomato	BHN 602’	602/Jjak	Drought tolerance	Nilsen *et al.*, (2014) [55]
Cucumber	Cucumber	Shintoza-type rootstock	Copper toxicity tolerant	Rouphael*et al.*, (2008) [65]
Cucumber	Cucumber (*Cucumis sativus* L. cv. Jinyan No. 4)	Luffa (*Luffa cylindrica* Roem. cv. Xiangfei No. 236)	Drought conditions	Liu *et al.* (2016) [43, 90]
Cucumber	Cucumber	Fig leaf gourd	Low temperature	Li *et al.*, (2014) [41, 42]
Cucumber	Cucumber	Pumpkin (*Cucurbita maxima* × *C. moschata*)	Nutrient deficiency or toxicity	Gao *et al.*, (2015) [21].
Cucumber	Cucumber cv. Jinchun No. 2	‘Chaojiquanwang’ rootstock (*C. moschata*)	Salinity tolerant	Huang *et al.*, (2013) [29]
Cucumber	Cucumber	Pumpkin	Salt tolerance	Xu *et al.*, (2017) [79]
Cucumber	Cucumber (*Cucumis sativus* L. cv. ‘Xintaimici’)	Three rootstock cultivars (Kilameki, Tielizhen, and Figleaf gourd	Low temperature	Li *et al.*, (2015)
Cucumber	cucumber	Luffa [*Luffa cylindrica* (L.) M. Roem] rootstock	Heat stress tolerance	Li *et al.* (2014) [41, 42]
Cucumber	cucumber	Luffa rootstock	Drought tolerance	Liu *et al.*, (2016) [43, 90].
Watermelon	*Citrulluslanatus* (Thunb.) Matsum. and Nakai, cv. Zaochunhongyu	Hongdun (*C. lanatus* sp.)	Potassium Deficiency Tolerant	Huang *et al.*, (2013) [29]
Watermelon	(Charleston Gray)	*Cucurbita pepo*	Drought tolerant and length of roots, number of leaves were significant high	Elsheery *et al.*, 2020 [18]
Muskmelon	Melons	*Cucurbita maxima* × *C. moschata*	Salt tolerant	Ulas*et al.*, (2019) [77]
Muskmelon	melon	*Cucurbita* rootstock	Nutrient deficiency tolerant	Neocleous, (2015) [53]
Sweet pepper	*cv.*Herminio	Creonte	Drought stress Tolerant	Lopez-Marín*et al.*, (2017) [44].

Table 6: Root stocks for abiotic stress:

Crop	Species	Specific features
Tomato	*Solanum pennelli*	Tolerance to drought (Bolger *et al.*, 2014) [12] and salt (Shalata *et al.*, 2001) [72]
Tomato	*S. chessmanii*	Resistant to salt (Rush and Epstein, 1976) [66]
Tomato	*S. chilense*	Resistance to drought
Brinjal	*S. macrocarpon*	Tolerant to flooding (Bhatt *et al.*, 2014) [10]
Brinjal	*Solanum elaeagnifolium*	Resistant to drought (Christodoulakis*et al.*,2009) [15]
Cucumber	*Cucurbita maxima x cucurbita*	Tolerant to high temperature (Lee *et al.*, 2010) [36, 37, 39] moschata
Potato	*Solanum cardensi*	Low temperature

Table 7: Quality breeding through vegetable grafting.

Crop name	Scion	Rootstock	Features	Reference
Tomato	Corbarino	Dinafort	increased fresh and dry yield, harvest index, and fruit/clusters	Parisi *et al.* (2022) [62]
Tomato	Corbarino	Silex	high levels of simple sugars, flavonoids, ascorbic acid, and trans-lycopene were also observed	Parisi *et al.* (2022) [62]
Eggplant	*S. torvum*	‘Birgah’ eggplant	increase Iodine-stress tolerance of eggplant, mproved total anthocyanins concentration	Consentino *et al.* (2022) [16]
Melon	Cantaloupe and honeydew melons	Carnivor	Root stock ‘Carnivor’ improved ascorbic acid content in grafted cantaloupe and honeydew melons, Root stock ‘Carnivor’ improved β-carotene content in grafted cantaloupe melons.	Lecholocholo *et al.* (2022) [35]

Future knowledge necessary to grafting
Rootstock information is limited: There is insufficient information on the usage of alternative rootstocks, compatibility with open-field cultivars, and field performance of grafted seedlings in various climates.

a) Automation technology: Grafting in herbaceous plants necessitates automation in order to generate grafted seedlings for commercial purposes on a big scale. Several agricultural businesses have developed semi- or completely automated grafting robots, and certain models are already available in East Asia, Europe, and the United States. For commercial purposes, the new attentiveness must be developed.

b) High production costs: The high cost of grafted seedlings is due to the high labour input required for propagation, the lengthier manufacturing phase, and the additional rootstock costs. These costs frequently deter potential consumers of grafted seedlings.

Conclusion and future thrust
Considering the diverse applications of vegetable grafting

worldwide, this technology has the potential to help India's vegetable industry overcome its challenges and increase farmers' income by increasing crop production and lowering the cost of fertilizers, pesticides, and disease control products. Grafting is an environmentally friendly method of promoting organic vegetable production. Watermelon grafted on interspecific cucurbit rootstocks increase pulp firmness, but melon loss of firmness can reflect latent rootstock–scion incompatibility. Fruit sweetness, induced by soluble carbohydrates whose concentration is susceptible to the effects of grafting, is arguably the most essential sensory quality. Changes in melon starch content and the relative proportions of hexoses to sucrose may be caused by rootstock-mediated changes in sweetness. It takes a lot of time and effort to grow and run a nursery. To address this issue, scientists must concentrate on inventing and popularising facilities, equipment, and grafting robots that will improve grafting efficiency while lowering labour costs. The development of databases, software, mobile applications, and crop models related to grafted vegetables will assist nursery managers and farming communities in the selection of suitable scion and rootstock cultivars. Grafted transplant trading is increasing rapidly on the international market, and with the development of the grafted vegetable industry in India, this option can be taken advantage of. Vegetable grafting is a cutting-edge approach for building climate resilience by minimizing soil degradation and natural resource loss, hence improving long-term vegetable production. More attention should be placed on implementing this strategy on a large scale, particularly amongst farmers, in order to promote a long-term, cost-effective, and year-round vegetable production.

Authors Contribution

PN: corresponding author of the manuscript, SS: General table for work conducted on Vegetable grafting, KKB: Information collected on biotic stress breeding-vegetable grafting, SJ: Information collected on quality breeding, DH: Information collected on Abiotic stress breeding-vegetable grafting. BK, NSG and SSM: Information collected on Abiotic stress breeding-vegetable grafting

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