Spanish Journal of Agricultural Research
21 (3), e0904, 13 pages (2023)
eISSN: 2171-9292
https://doi.org/10.5424/sjar/2023213-19793
INIA-CSIC

RESEARCH ARTICLE

OPEN ACCESS

Trends and gaps in tomato grafting literature: a systematic approach

Elen P. P. BENTO-DA-SILVA[1], Sara R. MENDONÇA[1] and Moemy G. DE MORAES[2*]

[1] *Programa de Pós-graduação em Agronomia, Universidade Federal de Goiás, Av. Nerópolis, s/n, Campus Samambaia, Goiânia, Goiás, Brazil.* [2] *Instituto de Ciências Biológicas, Universidade Federal de Goiás, Av. Esperança, s/n, Campus Samambaia, Goiânia, Goiás, Brazil.*

*Correspondence should be addressed to Moemy G. Moraes: moemy@ufg.br

Abstract

Aim of study: To investigate the trends and existing research gaps in tomato grafting by employing scientometric methods.

Area of study: In silico at SCOPUS database.

Material and methods: Research articles were retrieved by combining the search terms related to tomato and grafting. The articles were selected according to pre-established criteria. Temporal trends and scientometric indexes were determined. Bibliometric mappings were conducted to determine the main countries, authors, and journals that published articles on tomato grafting; and to acquire collaboration and keywords co-occurrence networks. Technical aspects of tomato grafting were analyzed.

Main results: A total of 397 research articles published from 1944 to 2020 were analyzed. The number of publications on tomato grafting increased at an annual rate of 8.8%. The USA and Spain are notable in terms of the number of published and cited articles. The USA and European countries had the highest number of collaborations. European authors had the strongest research connections. Interspecific grafts (61.83%) and experiments in controlled conditions (82.87%) predominated. The growing interest in tomato grafting has been observed as a means of overcoming environmental issues as well as yield and quality improvement.

Research highlights: Collaboration among research groups contributed to a higher research impact on the theme. The mitigation of abiotic stresses and fruit quality has risen as significant concerns for tomato crops.

Additional key words: bibliometric analysis; graft; *Solanum lycopersicum* L.; research network; research partnership.

Abbreviations used: FAOSTAT (Food and Agriculture Organization Corporate Statistical Database); NMDS (non-metric multidimensional scaling); UK (United Kingdom); USA (United States of America).

Citation: Bento-da-Silva, EPP; Mendonça, SR; de Moraes, MG (2023). Trends and gaps in tomato grafting literature: a systematic approach. Spanish Journal of Agricultural Research, Volume 21, Issue 3, e0904. https://doi.org/10.5424/sjar/2023213-19793

Supplementary material (Tables S1-S5) accompanies the paper on SJAR's website.

Received: 19 Aug 2022. **Accepted:** 24 Jul 2023.

Funding agencies/institutions	Project / Grant
Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES, Brasília, Brazil)	88887.688626/2022-00 88887.499650/2020-00

Competing interests: The authors have declared that no competing interests exist.

Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most produced and consumed vegetables worldwide. World's production of tomatoes is 180.8 million tons from 5 million hectares (FAOSTAT, 2019). In addition to being an essential component of the human diet, the tomato is a functional fruit and has been reported to prevent cardiovascular and cancerous diseases (Djidonou et al., 2016). Tomato production faces several constraints, including biotic and abiotic stresses and heterogeneity of the cultivation areas due to the vast worldwide production. However, to overcome these issues, the use of breeding tolerant cultivars is a time-consuming strategy.

Grafting is a horticultural technique used worldwide that combines two different plants; one used as a scion and the other as a rootstock (Mudge et al., 2009). This technique may provide tolerance to unfavorable conditions, whether biotic or abiotic, through the rootstock attributes and simultaneously allows the expression of the graft's production attributes. Thus, grafting can be used as an alternative technique to overcome the limitations of vegetable production.

In recent years tomato grafting has increased worldwide. One of the most classic objectives of grafting is disease control, which mainly focuses on soilborne diseases (Rivard & Louws, 2006). Initially, it was employed to control soil pathogens as an alternative to methyl bromide in protected environments (McAvoy et al., 2012). Moreover, the potential of tomato grafting is being employed in other crop issues as well, especially related to abiotic constraints, such as salinity (Coban et al., 2020), thermal stress (Han et al., 2019), nutrient absorption, translocation (Savvas et al., 2017), heavy metals (Xie et al., 2020) and water deficit (Zhang et al., 2020). Additionally, improving fruit quality is another advantage of tomato grafting (Djidonou et al., 2016).

Although tomato grafting has many advantages for crop cultivation, some challenges must be addressed. The grafting in the tomato plant is a very delicate process as the stem of the seedling is fragile. This process includes a few critical points such as insertion angle and position, the crown and diameter of rootstock, and phytosanitary quality (Bausher, 2011; 2013). The grafting execution requires trained individuals to ensure a higher rate of survival. Furthermore, taxonomic compatibility is another issue that is still poorly understood (Pina & Errea, 2005). In tomato plants, graft compatibility is limited to a few Solanaceae species such as potato (Arefin et al., 2019), eggplant (Xie et al., 2020), tobacco (Tunçay Çağatay et al., 2020), wolfberry (Feng et al., 2019), and some other *Solanum* species (Badawy et al., 2020; Carvalho et al., 2020).

Grafting has potential in tomato crop cultivation; it is crucial to understand the development of research in tomato grafting. Singh et al. (2017) provided a global perspective to the literature on tomato grafting and described agronomic aspects and the impacts of this technique on tomato cultivation in a narrative review. The application of scientometry allows the assessment of scientific publications obtained systematically and enables the highlighting of trends and contributions of various research groups working for scientific and technological advancement (Dalpé, 2002). This approach allows the quantitative evaluation of the research in a particular area (Ellegaard & Wallin, 2015) and provides an overview of the existing studies. The analysis of the temporal trends, the relationship among researchers and countries conducting similar kinds of research, as well as other aspects of scientific publications can be explored using scientometry. Therefore, we conducted a systematic review and used scientometric tools to understand the structure and organization of scientific literature in tomato grafting.

The objectives of the current study include (i) understanding the increased number of studies in tomato grafting over time; (ii) exploring the main contributing authors, countries, and research journals that published in tomato grafting; (iii) understanding the level of collaboration among research groups; (iv) to get an overview of the trends, gaps and technical characteristics in tomato grafting. Thus, the study was designed to provide scientific knowledge and technical development for tomato grafting, which can assist the academic-scientific community in building research networks. Additionally, the outcome of this study provides technical information to help the decision-making process in tomato grafting.

Table 1. Eligibility criteria for selecting the articles published in tomato grafting (1944–2020). The data were retrieved from the Scopus database.

Criteria	Articles
Retrieved from the database	1285
Duplicate	9
Grafting in other species	158
Studies in languages other than English	72
Studies in humans and animals	39
Studies in tomatoes for other purposes than grafting	345
Non-experimental publications and reviews	63
Studies that used tomatoes only as rootstock	139
Studies on rootstock characterization, but without grafting	63
Total of selected articles	397

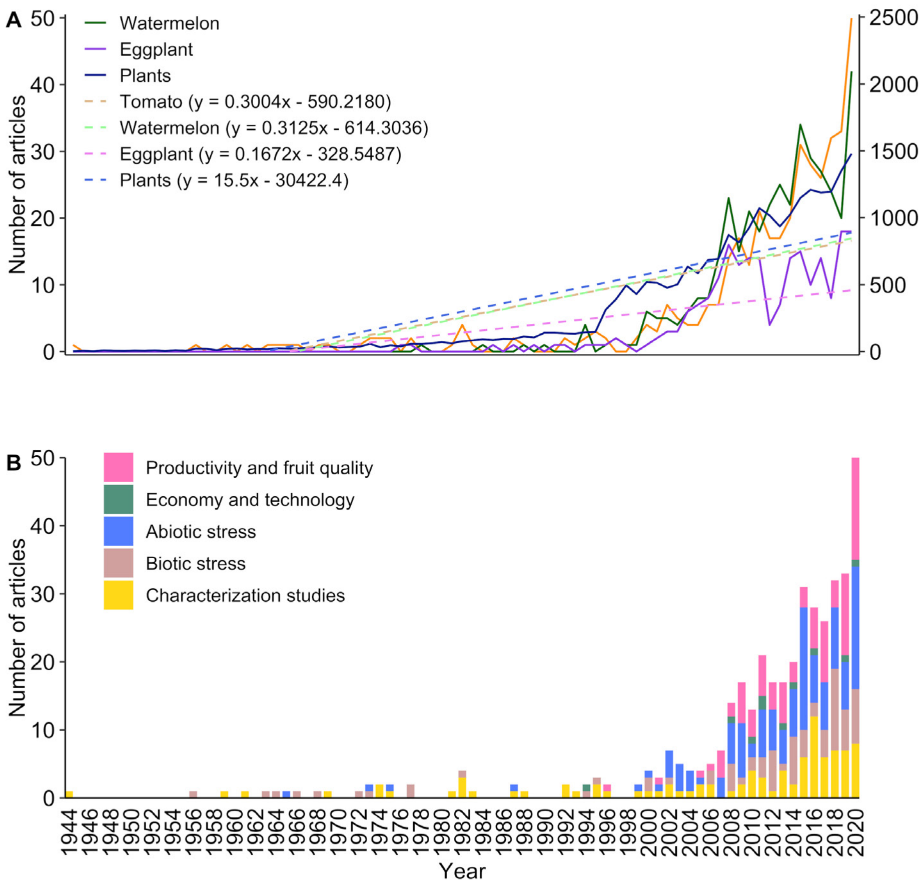

Figure 1. Illustration of the temporal trends in tomato grafting. (A) Temporal trends in the number of articles on tomato, watermelon, eggplant, and all plants grafting. Continuous lines represent the number of papers distributed for each species. Dashed lines represent the regression obtained for each set of publications. The y1 axis represents the number of publications in tomato, eggplant, and watermelon, and the y2 axis represents the number of publications in the Plants group. (B) Annual distribution of articles in tomato grafting, distributed according to number and purposes from 1944 to 2020

Material and methods

Database survey and articles selection

A database search was conducted for available research articles on tomato grafting from Scopus (https://www.scopus.com/), which has broader coverage (Pranckute, 2021). The query: TITLE-ABS-KEY ("GRAFT*" OR "SCION*" OR "ROOTSTOCK*" OR "STOCK*") AND TITLE-ABS-KEY ("TOMATO*" OR "LYCOPERSICUM ESCULENTUM" OR "SOLANUM LYCOPERSICUM" OR S. LYCOPERSICUM" OR "L. ESCULENTUM) was used for the search. An asterisk was used to replace the plurals and terms derived from the word. The database search using the above query was performed on November 11th, 2021, which resulted in 1285 publications from 1944 to 2020. The metadata including authors, year of publication, journals, citations, country, and author's keywords, were collected.

All the retrieved data were uploaded on Rayyan (https://www.rayyan.ai/) (Ouzzani et al., 2016), and the duplicates were removed. Initially, the selection of articles was performed independently by two collaborators following the eligibility criteria (Table 1). The second step involved the resolution of conflicts by the third collaborator individually. Finally, 397 publications were obtained at the end of the selection process (Table S1 [suppl]).

Temporal trends

The temporal trends in the number of published articles per year were analyzed. Each article was framed based on the central goal: productivity and quality of fruit, economy and technology, abiotic stress, biotic stress, and characterization studies. The temporal trends in tomato grafting were compared with all plant species and two relevant species in vegetable grafting: watermelon and eggplant (Lee et al., 2010). Additional surveys were performed to achieve this by replacing the tomato terms for “PLANT*”, for all plants; “WATERMELON*”, “CITRULLUS LANATUS”, OR “C. LANATUS” for watermelon and “EGGPLANT*”, “SOLANUM MELONGENA”, OR “S. MELONGENA” for eggplant. T-test was performed to compare the number of publications in tomato and other three groups (plants, watermelon, and eggplant) as well as linear regression between years and number of publications of each group.

Bibliometrics analyses

The collaboration index (Koseoglu, 2016) and authors index (Aria & Cuccurullo, 2017) were determined. Also, the ten most productive countries, the ten most cited articles, and journals with at least ten published articles were mapped. These analyses were conducted using the Bibliometrix package 3.0.5 (Aria & Cuccurullo, 2017) in software R 4.1.2 (R Core Team, 2020).

Co-authorship network mapping was built for authors and countries with at least five articles having five citations. In the co-occurrence network mapping, the query terms from the author’s keywords were removed, with keywords included in at least five articles. The links and link strength represent the number of connections from one item to others and the strength of those connections, respectively. All the network mappings were prepared using the VOSviewer 1.6.16 (van Eck & Waltman, 2010).

Characterization of tomato grafting

Each article was evaluated separately to obtain technological trends in grafting, identification of the main rootstocks, grafting methods, cultivation environment, and grafting specificity. The relation between grafting methods and countries was visualized using non-metric multidimensional scaling (NMDS) plots based on Bray-Curtis dissimilarity matrices employing vegan package 2.6-2 (Oksanen et al., 2022) in software R 4.1.2 (R Core Team, 2020).

Results

Temporal trends

In tomato grafting, the number of research articles increased at an annual rate of about 8.8%. These number differed from the tendency observed for all plants grafting ($t = -6.2943$; $p < 0.001$) from 1944-2020 (Fig. 1A). However, while comparing the number of articles in vegetable grafting (Fig. 1A), tomato grafting had similar tendencies as watermelon ($t = 0.0745$; $p = 0.9407$), and eggplant ($t = 1.8618$; $p = 0.06522$).

Until the end of the 20th century, only 10% of the articles on tomato grafting were published inconstantly (Fig. 1B). Over this period to 2020, a significant increase has been observed in the number of publications concurrently analyzing the response of grafted tomatoes to abiotic

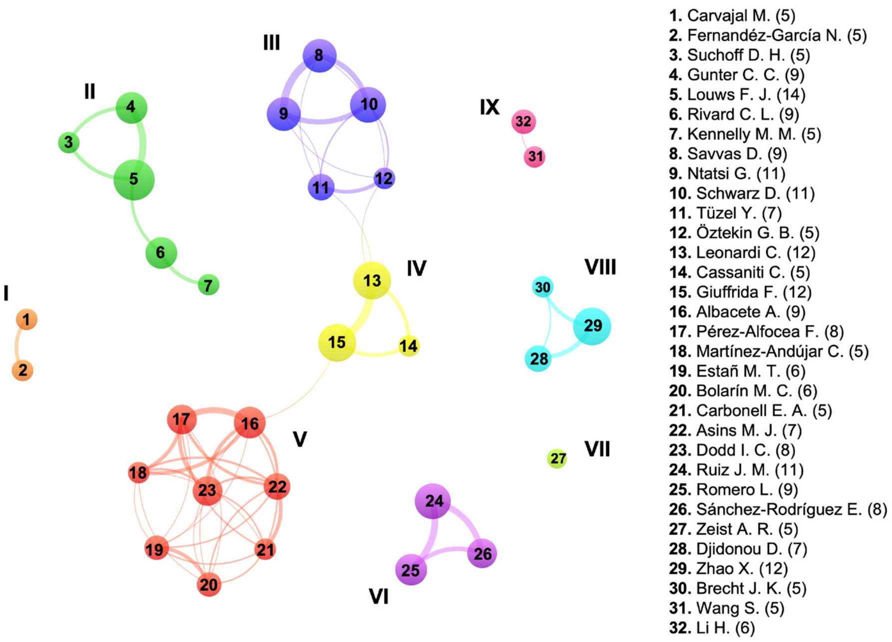

Figure 2. Co-authorship network mapping of the authors. The circle size and thickness of the links are proportional to the number of articles and link strength between the authors, respectively. The number of articles published by each author is indicated in parentheses. Roman numerals indicate clusters.

stresses as well as productivity and fruit quality. Since the beginning of this historical series evaluated, studies on the characterization of tomato grafting and its application in response to biotic stresses have been subject to constant accomplishment. The economic and technological aspects of tomato grafting were barely published over the years.

Authors and countries

Although 1240 authors were identified, only sixteen authors produced articles (17) with single authorship (Table S2 [suppl]). The author's index per article and collaboration index were 3.12 and 3.21, respectively. The co-authorship network resulted in nine clusters, i.e., I (nodes 1–2), II (nodes 3–7), III (nodes 8–12), IV (nodes 13–15), V (nodes 16–23), VI (nodes 24–26), VII (node 27), VIII (nodes 28–30), and IX (nodes 31–32) (Fig. 2). The group of Leonardi – Giuffrida, Savvas – Ntatsi, and Louws – Gunter shared the strongest link. The author with the highest number of articles is Louws F. J. (North Carolina State University, USA), with 14 publications.

Authors from 53 countries published research articles on tomato grafting (Table S2 [suppl]). The USA held the highest number of published articles on tomato grafting (261), followed by Spain (255) (Fig. 3A). These countries also hold the highest citations in 2013 and 2019, respectively. Co-authorship networks among countries resulted in five clusters: I (nodes 1–7), II (nodes 8–10), III (nodes 11–13), IV (nodes 14–18), and V (node 19) (Fig. 3B). The USA had the most significant number of collaborations.

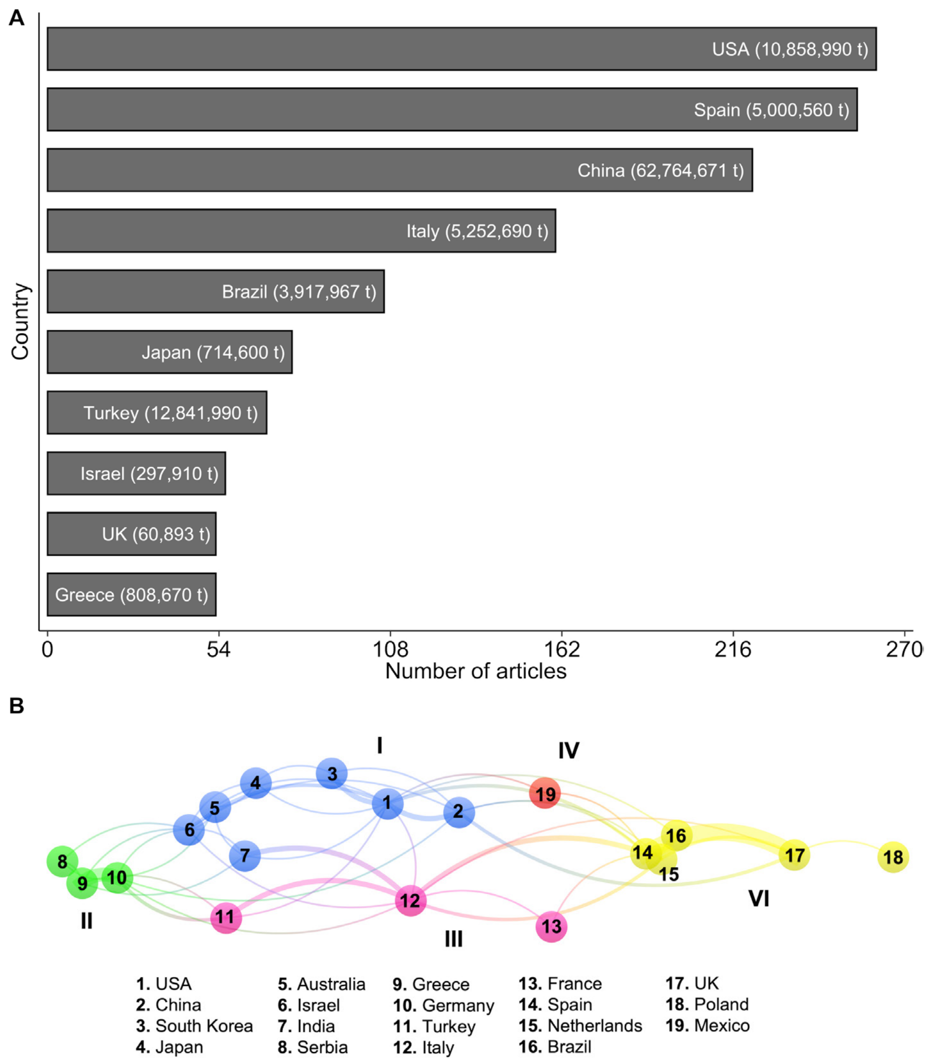

Figure 3. Publication ranking and partnership between countries in tomato grafting. (A) Scientific production per country based on participation in research articles in tomato grafting. The parentheses show tomato production in 2019 (FAOSTAT, 2019). (B) Co-authorship network mapping of countries. The circle size and thickness of the link are proportional to the number of articles and link strength between the countries, respectively. Roman numerals indicate cluster.

The strongest links were found between Spain and the UK, as well as Greece and Germany.

Journals and main papers

The surveyed research articles were published in 153 journals (Table S2 [suppl]), and the journal Acta Horticulturae (56) published the highest number of articles on tomato grafting (Fig. 4). There were only five journals that published ten or more articles on the subject. Although the whole set of articles has been cited 7367 times (Table S1 [suppl]), 69 articles (16.95%) were not cited by any researcher till 2020. There were only 11 articles (2.7%) with more than 100 citations. The articles with the highest number of citations were Li et al. (2002), Alvarez et al. (2006), Kim et al. (2001), Holbrook et al. (2002), and Estañ et al. (2005) with 301, 300, 291, 253 and 241 citations respectively (Table S3 [suppl]).

Authors' keywords

The selected articles contained 931 author's keywords (Table S2 [suppl]), and these keywords constituted eight clusters (Fig. 5), i.e., I (nodes 1-4), II (nodes 5-7), III (nodes 8-11), IV (nodes 12-14), V (nodes 15-16), VI (nodes 17-19) and VII (nodes 20-23) and VIII (nodes 24-26). The terms were related to the classification groups with built-in temporal trends analysis. The most used term was "yield" which has a considerable connection with "quality" and "fruit quality". Other strong connections were "fruit quality" with "salt stress", "vitamin C" with "Lycopene", and "*Ralstonia solanacearum*" with "bacterial wilt".

Technical characteristics of tomato grafting

The interspecific grafts (61.83%) and experiments conducted in controlled conditions (82.87%) predominated on tomato grafting publications (Table S4 [suppl]). Although fourteen grafting techniques were found in the selected papers (Table S4 [suppl]), 33.25% of papers did not specify the grafting method used in the experiments. The most used grafting methods in most countries were reported as splice (39.55%) and cleft (22.42%) (Fig. 6). In the studies, the primary commercial rootstocks used were Maxifort (16.88%) and Beaufort (14.61%) hybrids from De Ruiter, Bayer® (Table S5 [suppl]). A total of 285 rootstocks (68.83%) were used only once, and eighty-five were not precisely identified. The most used rootstock (76.83%) was observed as *S. lycopersicum* × *S. habrochaites*. In the interspecific grafting, the most used species as rootstock were *Solanum melongena* (7.37%), *Solanum tuberosum* (4.18%), *Nicotiana tabacum* (3.44%), *Solanum habrochaites* (3.44%), and *Solanum pimpinellifolium* (3.44%).

Discussion

Bibliometrics information

Tomato grafting studies are relevant among vegetables, as shown by the comparison of the temporal trends of stud-

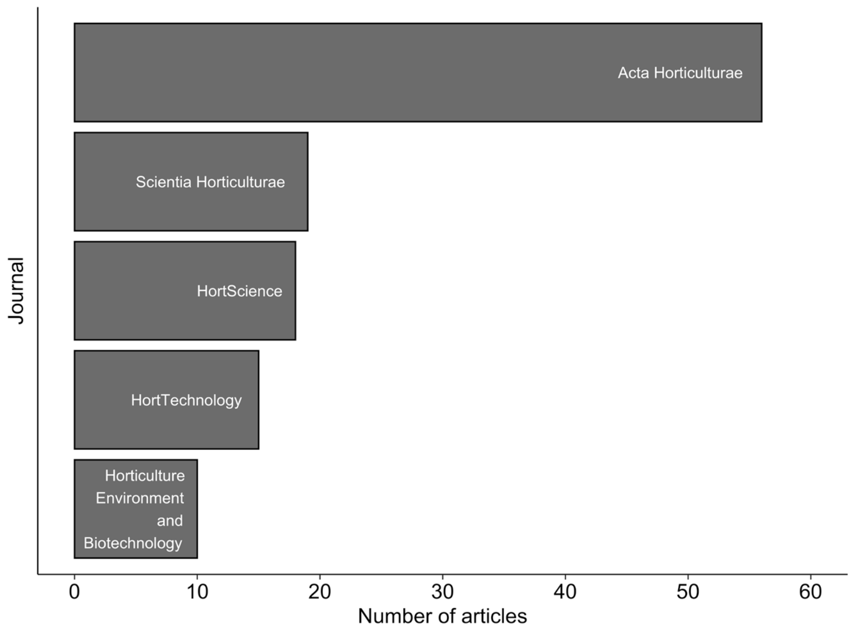

Figure 4. The ranking of key journals that published at least ten research articles in tomato grafting from 1944 to 2020.

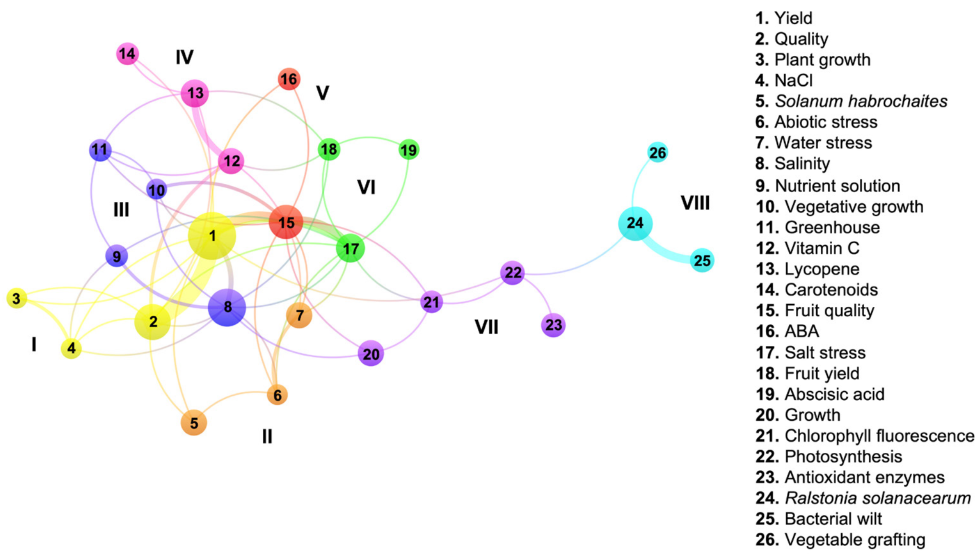

Figure 5. Co-occurrence network mapping of the thirty main author's keywords. Circles' size and thickness are proportional to the number of articles and the link strength between the author's keywords, respectively. Roman numerals indicate clusters.

ies on watermelon and eggplant grafting. There has been an observable increase in the number of publications on tomato grafting, in line with the global growth in scientific research (King, 2004; Nabout et al., 2015). However, the articles on tomato grafting represent only a tiny portion of grafting studies as most articles are focused on fruit trees and other plant species. Grafting has been used in fruit trees for a long time before its application in commercial production. In 1927, this technique was adopted in Korea and Japan for vegetables (Sakata et al., 2007). The use of grafting in tomato plants began in the 1960s (Bie et al., 2017). Three decades later, the use of vegetable grafting arose in Western countries (Lee et al., 2010).

Compared to the 2,982 journals indexed in Scopus under the category of "Agriculture and Biological Sciences", the number of journals that published articles on tomato grafting is relatively low at 153. However, this number can be considered satisfactory given the broad scope of the category and the specificity of tomato grafting within agricultural research. Tomato grafting has predominantly been published in horticultural journals. Within the "horticulture" category, 25 journals published a collection of 112 articles, representing 42.21% of the total. This indicates that interest in the grafting technique extends beyond the horticulture area and encompasses more than just production issues. Journals from other fields, such as plant physiology, have also published articles on tomato grafting, indicating interdisciplinary interest in the subject. The collection includes many studies on the movement of substances and signaling between roots and shoots. Regardless of the specific subject area, the peer-review process of specialized journals involves subject matter experts, ensuring a high degree of refinement in the published content.

Network analysis was used to examine the relationships between authors and countries within a specific topic. They showed that although numerous authors and countries published their research findings on tomato grafting, few had research collaborations. Only a few authors are part of the co-authorship network because many of them have published independently or in a restricted group with limited and disconnected partnerships. The clusters represented the research groups of different countries, i.e., clusters I, VI, and V: Spanish groups (cluster V having a British author), clusters II and VIII belong to the USA, cluster IV is an Italian research group, cluster VII composed of the single author from Brazil and cluster IX of Chinese researchers. Cluster III was the most heterogeneous, with researchers from Greece, Germany, and Turkey.

A higher number of articles have been published from countries having collaboration among research groups compared to countries without collaboration. Among European authors, the three main interconnected groups have a high level of cooperation, resulting in a greater number of published articles. In contrast, the low level of connectivity among research groups from other countries is reflected in the author's network and productivity analyses. Only nineteen countries have integrated co-authorship networks. The USA profile reflects the influence of connectivity between countries and scientific production: it has more collaborations and, consequently, published the highest number of articles. USA, Israel, and Italy have numerous connections suggesting a high level of partnership with other countries. Only USA, Spain, and China contributed to over half of the papers. Co-authorship networks between authors from Spain and UK, as well as Greece and Germany, illustrated the close relationships between authors and strong relationships among these countries.

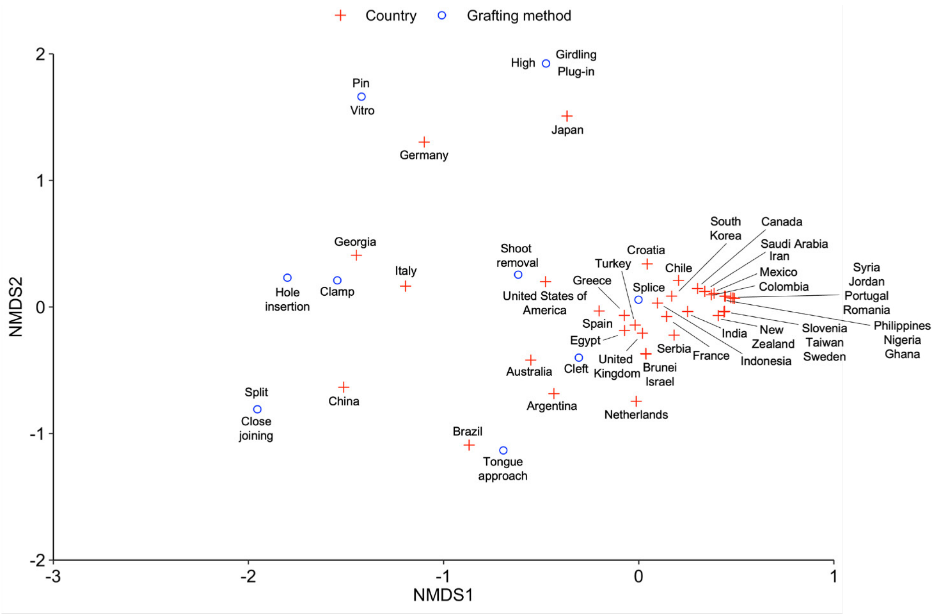

Figure 6. Non-metric multidimensional scale (NMDS) analysis relating the grafting methods (circle) and country (cross) of the corresponding authors.

A significant number of journals publishing articles on grafting are interdisciplinary in nature with multi-authored articles. Such interdisciplinary research requires collaboration among a team of researchers from diverse fields, who work together to integrate findings from their respective areas. This approach facilitates scientific and technological advancement by addressing complex and pertinent problems (Fortunato et al., 2018). According to Wuchty et al. (2007), multi-authored articles generally have more citations. Interdisciplinary partnerships can contribute to developing agricultural practices that increase tomato productivity since the prominent tomato-producing countries have research groups in the co-authorship network. Therefore, expanding partnerships and interdisciplinarity research is essential to achieve advancement in tomato grafting.

In contrast, the research groups with limited collaborations and independent authorship may limit the research development. In the case of tomato grafting, independent authorship or restricted partnerships may be associated with local demands and specific challenges for cultivation (Nkansah et al., 2013; Kakabadze, 2018). However, the sharing of challenges, techniques, equipment, and other tools among researchers, even in local demands, contribute to disseminating science and advanced agricultural practices (Nabout et al., 2015; Parreira et al., 2017; de Bem Oliveira et al., 2019).

Scientific trends in tomato grafting

Studies on the effects of abiotic stress in grafted tomatoes have stood out. Many investigations focused on the genetic, molecular, and physiological responses to abiotic stresses exploring it from the molecular to the crop level, as well as the use of grafting to minimize the negative impacts on tomato production. Tomato crops are sensitive to various climatic factors. As a result, a decrease in agricultural water supplies poses a significant threat to tomato production, affecting the entire production chain and reducing its availability to consumers (Badawy et al., 2020; Araya et al., 2021). The increased periods of drought and unreliable precipitation result in a water deficit for crop production. Abiotic factors such as drought and salinity have become significant concerns for tomato crops. There are reports of using grafted tomatoes as a relevant strategy to mitigate the effects of abiotic factors with potential applications in tomato production.

Grafting has been reported to be effective in reducing or even avoiding the damage caused by salinity (Zhu, 2016). There is a particular concern because tomato cultivation in protected environments and hydroponics requires intensive use of fertilizers which may increase the salinity (Coban et al., 2020). The accumulation of solutes, mainly Na^+ and Cl^-, in roots affects the plant's water status by decreasing osmotic potential, reducing water uptake and stomatal conductance. In most cases, salinity and water deficit are concurrent, which intensifies the impairment of tomato production (Uddin et al., 2016).

Despite a recent focus on abiotic factors, stress from biotic factors remains a crucial area of research. It is of paramount importance in tomato cultivation to deal with pathogenic organisms. Whereas the tomato crop is especially susceptible to soil pathogens, tomato grafting has been successfully used to provide resistance against nematodes, bacteria, and viruses by rootstock characteristics (Rivard et al., 2010; Louws et al., 2018). Mitigating soil pathogens has been a key focus in biotic stress studies, with special attention given to bacterial wilt caused by *Ralstonia solanacearum*, a critical Solanaceae disease in tropical climates (Carvalho et al., 2020). Of the biotic stress studies evaluated, 31.82% aimed to mitigate damage from bacterial wilt.

The characterization of physiological mechanisms using the grafting technique has been present in investigations on grafted tomato plants. The initial studies focused on understanding the connection between rootstock and scion (Pal & Nath, 1944). The complexity of these studies increased over the years, including genetics and molecular biology. The most cited articles in the collection belonged to this category, as they elucidate the grafting mechanism (Kim et al., 2001; Holbrook et al., 2002; Li et al., 2002; Estañ et al., 2005; Alvarez et al., 2006). Some studies provided information on the taxonomic compatibility between species (Zeist et al., 2017; Guimarães et al., 2019), while others defined the more effective grafting methods (Silva et al., 2016; Zeist et al., 2020). Reports provided information on the scion-rootstock connection, such as the cutting angle and the compatibility between the stem's diameters that contributes to improving the technique. The ideal cutting angle was reported at 50° and 70°, which provides intimate contact between the rootstock and scion, allowing the greater fixation force (Bausher, 2013; Pardo-Alonso et al., 2019a). After joining the rootstock and scion, adhesion occurs between them at the graft junction. The contact between rootstock and scion must be tight, as larger angles result in greater clamping force.

Plants have two poles, root, and shoot, interconnected by vascular tissues. The cutting disrupts this connection, collapses cells, and activates the plant responses to mechanical stress with a positional effect. The responses above the cut include increased auxin and sugar transport, signaling, and biosynthesis of brassinosteroids. However, the expression of stress response genes predominates below the cut. In contrast, genes for wound response, oxidative detoxification, lignin metabolism, and cell wall organization are co-expressed (Xie et al., 2019).

When the rootstock and scion are compatible, their ability to form new cells and tissues decides the union. The intact parenchymatic cells stick together at the graft interface, strengthening this connection over time. These cells produce callus, a mass of undifferentiated and pluripotent cells which divide intensely and get elongated (Fan et al., 2015). The cell wall becomes thicker at the adhesion area with the deposition of pectic material (Frey et al., 2020). This deposition occurs probably due to the increased secretion of β-1,4-glucanase in the extracellular region to facilitate cell wall reconstruction (Notaguchi et al., 2020). The callus proliferates until new cambial cells dedifferentiate and establish a continuous connection between the scion and the rootstock. The restitution of plasmodesmata enables simplastic movement. The peroxidase activity, an enzyme involved in the lignification process, increases significantly at this stage. Thus, the newly formed cells differentiate into vascular tissues, forming a vascular connection between the graft parts (Fan et al., 2015; Frey et al., 2020).

Quality and yield are the main keywords in the studies and have a strong connection. The influence of grafting on fruits' nutritional composition has also been well-studied (Djidonou et al., 2016). Nutrients such as lycopene, vitamin C, and carotenoids have been extensively studied. Consuming fresh tomatoes has numerous health benefits, including preventing cardiovascular diseases and cancer cell growth (Bhowmik et al., 2012). Research focuses on finding rootstocks that address fruit quality without impacting fruit quantity and biomass (Singh, 2017). In summary, studies show that the scion-rootstock combination directly affects tomato fruit quality.

Although studies on tomato grafting have several objectives, some topics, such as technological development, need to be further explored due to their relevance to the area. Only ten studies were found constituting the "economy and technology" topic. Grafting requires attention, precision, and training to ensure seedling survival. Incorrect execution requires additional seeds, increasing production costs and resulting in significant losses (Pardo-Alonso et al., 2019b). To ensure the grafting success, the angle and position of the cut, cleaning of the environment, as well as expertise of the methods are the key points. Reports show the possibility of automating grafting (Zhao et al., 2015; Pardo-Alonso et al., 2019b; 2020), which can maintain and even increase the survival rate of the grafted seedlings.

Cleft and splice methods have been used in more than 50% of the studies. These are the predominant methods used worldwide, as shown in the NMDS analysis. This study considered the cleft method because it is a synonym for the tube, slant-cut, splice, and wedge (Lee & Oda, 2010; Lee et al., 2010). Our analysis suggests the wide use of this technique in Cucurbitaceae and the commonly used method in Solanaceae (Lee et al., 2010). However, commercial production mainly uses tube grafting, which applies the clips to provide mechanical support for a solid connection between scion and rootstock, resulting in a high survival rate (Lee & Oda, 2010). The advantages of tube grafting include reduced cost and labor, and thus it is a straightforward technique. It can be considered for commercial tomato grafting (Rivard & Louws, 2006; Lee et al., 2010).

The rootstock is part of the graft which provides the desired characteristics. In addition, rootstocks need to be compatible with the scion without reducing plant growth and productivity (Albacete et al., 2015). Our analysis revealed that *Solanum habrochaites* is commonly used in commercial rootstocks and is a prominent species for interspecific grafts. This species is robust and widely used in crosses to obtain resistant traits (Sifres et al., 2011), which increases genetic variability and maintains compatibility as they belong to the same family. Moreover, the use of several cultivated species from the Solanaceae family as rootstocks were also identified in this study.

Interspecific grafts predominated in the analyzed reports. Though intraspecific grafting is recommended for compatibility, the tolerance characteristics may not be sufficiently shared between the same species (Venema et al., 2008; Rivard et al., 2010; Zeist et al., 2017). Using other species as rootstocks expands the diversity and genetic variability, providing tolerance to grafted plants compared to non-grafted tomatoes (Petran & Hoover, 2014). Compatibility tests demonstrate considerable benefits of using wild species for tomato grafting for various uses. Currently, 4020 species of the Solanaceae family have been recognized worldwide, from these, 1946 belong to *Solanum* (GBIF, 2021), demonstrating a great potential still underexploited for grafting.

This study applied scientometric methods to analyze the scientific production on tomato grafting for the first time. The most significant relations among different countries and research groups and their impact on the scientific production on the topic were presented. The analyses showed that tomato grafting has been used for the purposes of plant production, but it is also a promising technique to elucidate morpho-physiological processes. It was evident that tomato grafting shows potential for mitigating adverse environmental effects and for obtaining fruits of high quality. However, further studies are needed on the automation of processes, analysis in unprotected environments, the economic and environmental impacts in different locations around the globe, and on the testing of different species and genotypes for rootstocks. Finally, it is recommended that special attention be given to establishing collaboration between interdisciplinary groups in different countries to lead to advancements in the technique as well as scientific productivity and the impact of these studies.

Acknowledgments

The authors are grateful to Jascieli Carla Bortolini, Rogério M. Faleiros, and Rhewter Nunes for the critical review of the manuscript.

Authors' contributions

Conceptualization: E. P. P. Bento-da-Silva, M. G. Moraes
Data curation: E. P. P. Bento-da-Silva, M. G. Moraes, S. R. Mendonça
Formal analysis: E. P. P. Bento-da-Silva, M. G. Moraes
Funding acquisition: Not applicable
Investigation: E. P. P. Bento-da-Silva
Methodology: E. P. P. Bento-da-Silva, S. R. Mendonça
Project administration: M. G. Moraes
Resources: Not applicable
Software: Not applicable
Supervision: M. G. Moraes
Validation: E. P. P. Bento-da-Silva, M. G. Moraes
Visualization: E. P. P. Bento-da-Silva, M. G. Moraes
Writing – original draft: E. P. P. Bento-da-Silva
Writing – review & editing: E. P. P. Bento-da-Silva, M. G. Moraes

References

Albacete A, Andújar C, Dodd I, Giuffrida F, Hichri I, Lutts S, et al., 2015. Rootstock-mediated variation in tomato vegetative growth under drought, salinity and soil impedance stresses. Acta Hortic 1086: 141-146. https://doi.org/10.17660/ActaHortic.2015.1086.17

Alvarez JP, Pekker I, Goldshmidt A, Blum E, Amsellem Z, Eshed Y, 2006. Endogenous and synthetic microRNAs stimulate simultaneous, efficient, and localized regulation of multiple targets in diverse species. Plant Cell 18(5): 1134-1151. https://doi.org/10.1105/tpc.105.040725

Araya NA, Chiloane TS, Rakuambo JZ, Maboko MM, du Plooy CP, Amoo SO, 2021. Effect of environmental variability on fruit quality and phytochemical content of soilless grown tomato cultivars in a non-temperature-controlled high tunnel. Sci Hortic 288(110378): 1-15. https://doi.org/10.1016/j.scienta.2021.110378

Arefin SMA, Zeba N, Solaiman AH, Naznin MT, Azad MOK, Tabassum M, et al., 2019. Evaluation of compatibility, growth characteristics, and yield of tomato grafted on potato ('pomato'). Horticulturae 5(37): 1-9. https://doi.org/10.3390/horticulturae5020037

Aria M, Cuccurullo C, 2017. Bibliometrix: an R-tool for comprehensive science mapping analysis. J Informetr 11(4): 959-975. https://doi.org/10.1016/j.joi.2017.08.007

Badawy MA, Abdel-Wahab A, Sayed EG, 2020. Increasing tomato (*Solanum lycopersicum* L.) tolerance of water stress conditions by using some agricultural practices. Plant Arch 20(1): 2655-2676.

Bausher MG, 2011. Grafting technique to eliminate rootstock suckering of grafted tomatoes. Hortscience 46(4): 596-598. https://doi.org/10.21273/HORTSCI.46.4.596

Bausher MG, 2013. Graft angle and its relationship to tomato plant survival. Hortscience 48(1): 34-36. https://doi.org/10.21273/HORTSCI.48.1.34

Bhowmik D, Kumar KPS, Paswan S, Srivastava S, 2012. Tomato - A natural medicine and its health benefits. Phytojournal 1(1): 24-36.

Bie Z, Nawaz MA, Huang Y, Lee JM, Colla G, 2017. Introduction to vegetable grafting. In: Vegetable grafting: principles and practices; Colla G, Pérez-Alfocea F, Schwarz D, (eds.). pp: 1-21. CABI Publ, Wallingford. https://doi.org/10.1079/9781780648972.0001

Carvalho LTS, Melo DM, Vargas PF, Santos HCA, Ferreira JV, 2020. Tomato grafting onto Solanaceae genotypes to control bacterial wilt (*Ralstonia solanacearum* Smith 1896). Pesqui Agropecu Trop 50: e63476. https://doi.org/10.1590/1983-40632020v5063476

Coban A, Akhoundnejad Y, Dere S, Dasgan HY, 2020. Impact of salt-tolerant rootstock on the enhancement of sensitive tomato plant responses to salinity. Hortscience 55(1): 35-39. https://doi.org/10.21273/HORTSCI14476-19

Dalpé R, 2002. Bibliometric analysis of biotechnology. Scientometrics 55(2): 189-213. https://doi.org/10.1023/A:1019663607103

de Bem Oliveira I, Nunes R, Mattiello L, Barros-Ribeiro S, Souza IP, Coelho ASG, et al., 2019. Research and partnership in studies of sugarcane using molecular markers: a scientometric approach. Scientometrics 119(1): 335-355. https://doi.org/10.1007/s11192-019-03047-6

Djidonou D, Simonne AH, Koch KE, Brecht K, Zhao X, 2016. Nutritional quality of field-grown tomato fruit as affected by grafting with interspecific hybrid rootstocks. Hortscience 51(12): 1618-1624. https://doi.org/10.21273/HORTSCI11275-16

Ellegaard O, Wallin JA, 2015. The bibliometric analysis of scholarly production: how great is impact? Scientometrics 105: 1809-1831. https://doi.org/10.1007/s11192-015-1645-z

Estañ MT, Martinez-Rodríguez MM, Pérez-Alfocea F, Flowers TJ, Bolarín MC, 2005. Grafting raises the salt tolerance of tomato through limiting the transport of sodium and chloride to the shoot. J Exp Bot 56(412): 703-712. https://doi.org/10.1093/jxb/eri027

Fan J, Yang R, Li X, Zhao W, Zhao F, Wang S, 2015. The processes of graft union formation in tomato. Hortic Environ Biotechnol 56(5): 569-574. https://doi.org/10.1007/s13580-015-0009-1

FAOSTAT, 2019. On-line and multilingual database. Food and Agriculture Organization of the United Nations. http://faostat.fao.org/ [Oct, 2021].

Feng X, Guo K, Yang C, Li J, Chen H, Liu X, 2019. Growth and fruit production of tomato grafted onto wolfberry (*Lycium chinense*) rootstock in saline soil. Sci Hortic 255: 298-305. https://doi.org/10.1016/j.scienta.2019.05.028

Fortunato S, Bergstrom CT, Börner K, Evans JA, Helbing D, Milojevic S, et al., 2018. Science of science. Science 359(6379): 1-21. https://doi.org/10.1126/science.aao0185

Frey C, Acebes JL, Encina A, Álvarez R, 2020. Histological changes associated with graft union development in tomato. Plants 9(11): 1479-1492. https://doi.org/10.3390/plants9111479

GBIF, 2021. Solanaceae. The Global Biodiversity Information Facility. https://www.gbif.org/ [Oct, 2021].

Guimarães MA, Garcia MFN, Tello JPJ, Lemos-Neto HS, Lima-Neto BP, Rabelo JS, 2019. Tomato grafting on rootstock of Jilo, Cocona and Jurubeba. Hortic Bras 37: 138-145. https://doi.org/10.1590/s0102-053620190203

Han M, Cao BL, Liu SS, Sin, KX, 2019. Effects of rootstock and scion interactions on ascorbate-glutathione cycle in tomato seedlings under low temperature stress. Acta Hortic Sin 46(1): 65-73.

Holbrook NM, Shashidhar VR, James RA, Munns R, 2002. Stomatal control in tomato with ABA-deficient roots: response of grafted plants to soil drying. J Exp Bot 53(373): 1503-1514. https://doi.org/10.1093/jxb/53.373.1503

Kakabadze N, 2018. The peculiarities of vegetable grafting technology in Georgia. Bull Georg Nat Acad Sci 12(4): 125-129.

Kim M, Canio W, Kessler S, Sinha N, 2001. Developmental changes due to long-distance movement of a homeobox fusion transcript in tomato. Science 293: 287-289. https://doi.org/10.1126/science.1059805

King DA, 2004. The scientific impact of nations. Nature 430: 311-437. https://doi.org/10.1038/430311a

Koseoglu MA, 2016. Mapping the institutional collaboration network of strategic management research: 1980-2014. Scientometrics 109(1): 203-226. https://doi.org/10.1007/s11192-016-1894-5

Lee JM, Oda M, 2010. Grafting of herbaceous vegetable and ornamental crops. Hortic Rev 28(2): 61-124. https://doi.org/10.1002/9780470650851.ch2

Lee JM, Kubota C, Tsao SJ, Bie Z, Echevarria PH, Morra L, et al., 2010. Current status of vegetable grafting: diffusion, grafting techniques, automation. Sci Hortic 127(2): 93-105. https://doi.org/10.1016/j.scienta.2010.08.003

Li L, Li C, Lee GI, Howe GA, 2002. Distinct roles for jasmonate synthesis and action in the systemic wound response of tomato. P Natl Acad Sci USA 99(9): 6416-6421. https://doi.org/10.1073/pnas.072072599

Louws FJ, Suchoff D, Kressin J, Panthee D, Driver J, Gunter C, 2018. Integrating grafting and emerging products to manage soilborne diseases of tomato. Acta Hortic 1207: 249-254. https://doi.org/10.17660/ActaHortic.2018.1207.34

McAvoy T, Freeman JH, Rideout SL, Olson SM, Paret ML, 2012. Evaluation of grafting using hybrid rootstocks for management of bacterial wilt in field tomato production. Hortscience 47(5): 621-625. https://doi.org/10.21273/HORTSCI.47.5.621

Mudge K, Janick J, Scofield S, Goldschmidt EE, 2009. A history of grafting. Hortic Ver 35(9): 437-493. https://doi.org/10.1002/9780470593776.ch9

Nabout JC, Parreira MR, Teresa FB, Carneiro FM, Cunha HF, Ondei LS, et al., 2015. Publish (in a group) or perish (alone): the trend from single- to multi-authorship in biological papers. Scientometrics 102: 357-364. https://doi.org/10.1007/s11192-014-1385-5

Nkansah GO, Ahwireng AK, Amoatey C, Ayarna AW, 2013. Grafting onto African eggplant enhances growth, yield and fruit quality of tomatoes in tropical Forest ecozones. J Appl Hortic 15(1): 16-20. https://doi.org/10.37855/jah.2013.v15i01.03

Notaguchi M, Kurotani K, Sato Y, Tabata R, Kawakatsu Y, Okayasu K, et al., 2020. Cell-cell adhesion in plant grafting is facilitated by b-1,4-glucanases. Plant Sci 369: 698-702. https://doi.org/10.1126/science.abc3710

Oksanen J, Simpson GL, Blanchet FG, Kindt R, Legendre P, Minchin PR, et al., 2022. Vegan: community ecology package. R package version 2.6-2”. https://CRAN.R-project.org/package=vegan.

Ouzzani M, Hammady H, Fedorowicz Z, Elmagarmid A, 2016. Rayyan - a web and mobile app for systematic reviews. Syst Rev 5(210): 1-10. https://doi.org/10.1186/s13643-016-0384-4

Pal BP, Nath BV, 1944. The accumulation and movement of nicotine in reciprocal grafts between tobacco and tomato plants. Proc Ind Acad Sci 20(3): 79-87. https://doi.org/10.1007/BF03049792

Pardo-Alonso JL, Carreño-Ortega Á, Martínez-Gaitán CC, Callejón-Ferre ÁJ, 2019a. Combined influence of cutting angle and diameter differences between seedlings on the grafting success of tomato using the splicing technique. Agronomy 9(5): 1-15. https://doi.org/10.3390/agronomy9010005

Pardo-Alonso JL, Carreño-Ortega Á, Martínez-Gaitán CC, Golasi I, Galán MG, 2019b. Conventional industrial robotics applied to the process of tomato grafting using the splicing technique. Agronomy 9(880): 1-17. https://doi.org/10.3390/agronomy9120880

Pardo-Alonso JL, Carreño-Ortega A, Martínez-Gaitán CC, Fatnassi H, 2020. Behavior of different grafting strategies using automated technology for splice grafting technique. Appl Sci 10(2745): 1-15. https://doi.org/10.3390/app10082745

Parreira MR, Machado KB, Logares R, Diniz-Filho JAF, Nabout JC, 2017. The roles of geographic distance and socioeconomic factors on international collaboration among ecologists. Scientometrics 113(3): 1539-1550. https://doi.org/10.1007/s11192-017-2502-z

Petran A, Hoover E, 2014. *Solanum torvum* as a compatible rootstock in interspecific tomato grafting. J Hortic 1(1): 1-4.

Pina A, Errea P, 2005. A review of new advances in mechanism of graft compatibility- incompatibility. Sci Hortic 106: 1-11. https://doi.org/10.1016/j.scienta.2005.04.003

Pranckutė R, 2021. Web of science (WoS) and Scopus: the titans of bibliographic information in today's academic world. Publications 9(1): 1-12. https://doi.org/10.3390/publications9010012

R Development Core Team, 2020. R: A language and environment for statistical computing. Vienna, Austria. https://www.r-project.org/.

Rivard CL, Louws FJ, 2006. Grafting for disease resistance in Heirloom tomatoes. North Carolina Coop Ext Serv Bull Ag-675.

Rivard CL, O'Connell S, Peet MM, Louws FJ, 2010. Grafting tomato with interspecific rootstock to manage diseases caused by Sclerotium rolfsii and southern root-knot nematode. Plant Dis 94(8): 1015-1021. https://doi.org/10.1094/PDIS-94-8-1015

Sakata Y, Ohara T, Sugiyama M, 2007. The history and present state of the grafting of cucurbitaceous vegetables in Japan. Acta Hortic 731: 159-170. https://doi.org/10.17660/ActaHortic.2007.731.22

Savvas D, Öztekin GB, Tepecik M, Ropokis A, Tüzel Y, Ntatsi G, et al., 2017. Impact of grafting and rootstock on nutrient-to-water uptake ratios during the first month after planting of hydroponically grown tomato. J Hortic Sci Biotechnol 92(3): 294-302. https://doi.org/10.1080/14620316.2016.1265903

Sifres A, Blanca J, Nuez F, 2011. Pattern of genetic variability of *Solanum habrochaites* in its natural area of distribution. Genet Resour Crop Evol 58: 347-360. https://doi.org/10.1007/s10722-010-9578-0

Silva ES, Menezes DV, Silva EG, Goto R, Lima PP, 2016. Different methods of grafting and activity of antioxidant enzymes in tomato. Rev Bras Cienc Agrar 11(4): 267-271. https://doi.org/10.5039/agraria.v11i4a5392

Singh H, Kumar P, Chaudhari S, Edelstein M, 2017. Tomato grafting: a global perspective. Hortscience 52(10): 1328-1336. https://doi.org/10.21273/HORTSCI11996-17

Tunçay Çağatay S, Çalik Koç G, Rezaei F, Darcansoy Iseri O, Sahin FI, Haberal M, 2020. Evaluation of production conditions of tomato grafted with different tobacco rootstocks and determining nicotine content and quality of fruit. Acta Agric Slov 115(2): 297-305. https://doi.org/10.14720/aas.2020.115.2.1244

Uddin MN, Hossain MA, Burritt DJ, 2016. Salinity and drought stress: similarities and differences in oxidative responses and cellular redox regulation. In: Water stress and crop plants: a sustainable approach; Ahmad P (ed.). pp: 86-101. Wiley-Blackwell, New York. https://doi.org/10.1002/9781119054450.ch7

Van-Eck NJ, Waltman L, 2010. Software survey: VOSViewer, a computer program for bibliometric mapping. Scientometrics 84(2): 523-528. https://doi.org/10.1007/s11192-009-0146-3

Venema JH, Dijk BE, Bax JM, van Hasselt PR, Elzenga TM, 2008. Grafting tomato (*Solanum lycopersicum*) onto the rootstock of a high-altitude accession of *Solanum habrochaites* improves suboptimal-temperature tolerance. Environ Exp Bot 63(1-3): 359-367. https://doi.org/10.1016/j.envexpbot.2007.12.015

Wuchty S, Jones BF, Uzzi B, 2007. The increasing dominance of teams in production of knowledge. Science 316(5827): 1036-1039. https://doi.org/10.1126/science.1136099

Xie L, Dong C, Shang Q, 2019. Gene co-expression network analysis reveals pathways associated with graft healing by asymmetric profiling in tomato. BMC Plant Biol 19(373): 1-12. https://doi.org/10.1186/s12870-019-1976-7

Xie Y, Tan H, Sun G, Li H, Liang D, Xia H, et al., 2020. Grafting alleviates cadmium toxicity and reduces its absorption by tomato. J Soil Sci Plant Nutr 20(2): 1-8. https://doi.org/10.1007/s42729-020-00289-9

Zeist AR, Resende JTV, Giacobbo CL, Faria CMDR, Dias DM, 2017. Graft takes of tomato on other solanaceous plants. Rev Caatinga 30(2): 513-520. https://doi.org/10.1590/1983-21252017v30n227rc

Zeist AR, Resende JTV, Zanin DS, Silva ALBR, Perrud AC, Bueno GA, et al., 2020. Effect of acclimation environments, grafting methods and rootstock RVTC-66 on the seedling development and production of tomato. Sci Hortic 271(109496): 1-6. https://doi.org/10.1016/j.scienta.2020.109496

Zhang Z, Liu Y, Cao B, Chen Z, Xu K, 2020. The effectiveness of grafting to improve drought tolerance in tomato. Plant Growth Regul 91: 157-167. https://doi.org/10.1007/s10725-020-00596-2

Zhao X, Wang Z, Liu S, Wang R, Tian S, 2015. Grading system of tomato grafting machine based on machine vision. Proc 8th Int Congr on Image and Signal Processing, Shenyang (China), Oct 14-16. pp: 604-609. https://doi.org/10.1109/CISP.2015.7407950

Zhu JK, 2016. Abiotic stress signaling and responses in plants. Cell 167: 313-324. https://doi.org/10.1016/j.cell.2016.08.029