EVOLUTION AND TECHNOLOGICAL DEVELOPMENT OF AUTOMATIC TRANSPLANTERS FOR VEGETABLES: A REVIEW
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EVOLUCIÓN Y DESARROLLO TECNOLÓGICO DE LAS TRASPLANTADORAS AUTOMÁTICAS PARA HORTALIZAS: UNA REVISIÓN

Gaudencio GRANDE[1)], Martín HIDALGO-REYES*[2)], Pedro CRUZ[2)], Noe VELÁZQUEZ[3)]
[1)] Graduate Program of Agricultural Engineering and Integral Use of Water, Universidad Autonoma Chapingo / Mexico;
[*2)] Agricultural Mechanical Engineering Department, Universidad Autonoma Chapingo / Mexico;
[3)] Irrigation Department, Universidad Autonoma Chapingo / Mexico;
Tel: +525951104405; E-mail: mhidalgor@chapingo.mx
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ABSTRACT
The main purpose of technological progress is to enhance the quality of human life. In agriculture, there has been a trend towards automating all stages of production processes. Transplanting seedlings is no exception, as it involves a repetitive and laborious process that demands significant time, depending on the extension to be transplanted. The objective of this review article was to analyze the evolution and technological development of automated transplanter prototypes by bibliometric analysis and a detailed review. Results show that the technological progress in this equipment is based on two main characteristics: (1) physical-mechanical properties of seedlings, which play a crucial role in component design, and (2) control and automation development. This means that efficiencies of over 90% and an error rate of less than 7.6% can be currently obtained for automated transplanter.

RESUMEN
El avance tecnológico ha tenido como propósito principal mejorar la calidad de vida del ser humano. En la agricultura se ha optado por automatizar todas las fases de los procesos de producción. El trasplante de plántulas no es la excepción, debido a que es un proceso repetitivo y cansado, que requiere amplios periodos de tiempo según la extensión a trasplantar. El objetivo de este artículo de revisión fue analizar la evolución y desarrollo tecnológico de los prototipos de trasplante automático de plántulas, mediante un análisis bibliométrico y una revisión detallada. Los resultados muestran que el avance tecnológico desarrollado en estos equipos se basa en dos características principales: (1) las propiedades físico-mecánicas de las plántulas, como características sobresalientes en el diseño de los componentes y, (2) el desarrollo del control y la automatización, con lo cual, actualmente se pueden obtener eficiencias superiores a 90% y una tasa de error inferior al 7.6% en el trasplante automático de plántulas.

INTRODUCTION
The evolution and technological advancement of automatic transplanters for vegetable crops mark a significant milestone in modern agriculture. These machine designs serve as transformative tools, revolutionizing traditional transplanting methods by enhancing efficiency, cutting labor costs, and refining precision in the transplanting process *(Ahmed et al., 2024)*. In recent decades, there has been remarkable progress in both the design and functionality of automatic transplanters, propelled by advancements in engineering, robotics, and precision agriculture *(Bazargani & Deemyad, 2024)*.

Vegetables comprise a group of greens and fruits such as tomatoes and are grown in open fields and greenhouses, playing a crucial role in human nutrition. They serve as antioxidants, anticancer agents, antidiabetics, and aids in reducing cardiovascular diseases *(Dias, 2019; Radovich, 2018)*. The most economically important vegetables in the world are tomatoes, bell peppers, melons and zucchinis, eggplants, cucumbers, watermelons and strawberries *(Baudoin, 2002)*.

[1] *Gaudencio GRANDE, Doctoral Stud.; Martín HIDALGO-REYES, Professor, Ph.D.; Pedro CRUZ, Professor, Ph.D.; Noe VELAZQUEZ, Professor, Ph.D.*

Transplanting is one of the tasks that requires high labor and time costs. Hence, mechanizing this task is essential for efficient operations and increased production *(Nage et al., 2023).* Currently, the most advanced transplanting machines include both semi-automated and automated models.

In contemporary agriculture, applications of robots and automated transplanters are being employed to enhance the quality and efficiency of this operation. These technologies are based on different principles, such as visual processing, aiming to reduce the damage rate to stems, leaves, and substrates *(Jin et al., 2021)*.

Automated transplanters are commonly structured with three systems: supply, manipulation, and transplant *(Jin et al., 2018)*. However, the types vary based on the working environment. Some are stationary, like the one developed by *Han et al. (2018)* for potted seedlings in a greenhouse, while others are autonomous machines designed for transplanting in elevated greenhouse cultivation *(Liu et al., 2019)*. There are also autonomous machines specifically used for transplanting in open fields *(Han et al., 2019)*.

Furthermore, various review studies have delved into the advancement and progression of automatic vegetable transplanters. *Syed et al. (2019)* primarily delved into artificial vision technology's application in automatic transplantation, aiming to enhance time efficiency, quality, and overall effectiveness. *Rasool et al. (2020)* dissected the diverse mechanisms encompassing clamps, manipulators, and end effectors of mobile, semi-automatic, and automatic transplanters, focusing specifically on onion transplantation automation. Similarly, *Habineza et al. (2023)* undertook a comparable analysis, albeit for seedlings in a broader context. *Sharma & Khar, (2022)* conducted a comprehensive examination encompassing manual, mechanical, and automatic vegetable transplanters.

Moreover, several research endeavors have explored technology and robotics' integration in transplantation methodologies, emphasizing the significance of substrates, end effectors, vision systems, and route planning *(Liu et al., 2023; Sharma et al., 2023)*.

Researchers worldwide, including those mentioned above, publish their findings in various journals, which are indexed in different databases like Scopus and Web of Science (S&WoS). Consequently, research into automated vegetable transplanters follows this trend, being no exception. The process of searching for information in these databases relies on the use of keywords. The system then displays the located documents, which are subsequently filtered by adding more specific words. In this context, bibliometric analysis serves as a tool to condense and synthesize information. It facilitates the examination of key variables, including development trends over the years, emerging areas, and collaborations among authors from different countries *(Chen et al., 2021; Donthu et al., 2021)*.

The S&WoS platforms are not designed for conducting bibliometric analyses. Therefore, extracting bibliometric information from these databases can pose a disadvantage as they may contain adverse conditions such as data duplication, and they do not analyze specific data from the study conducted in each research *(Donthu et al., 2021)*, therefore, it is necessary to complement the information with an additional review of articles obtained from other databases. In other words, a comprehensive analysis of the information is required, evaluating, discussing, and interpreting advancements and areas of opportunity related to prototypes developed for automated vegetable transplanting.

Finally, the development and evolution of automatic transplanting equipment for vegetables have proven to be highly advantageous for modern agriculture. These advancements offer a range of significant benefits, including increased efficiency and reduced labor costs, enhanced precision in seedling transplantation, minimized risk of plant damage, adaptability to diverse crops, resource optimization, and improved working conditions in the field. Clearly, these technological strides are driving a more productive, sustainable, and profitable agricultural sector, poised to revolutionize the industry and bolster global food security. However, despite the notable progress in this research domain, there remain areas necessitating further analysis. Hence, the primary objective of this study is to analyze the evolution, technological development, and engineering characteristics of prototypes for automated vegetable transplanting over the years. The analysis of this research was carried out using two tools: bibliometric analysis and a detailed review.

MATERIALS AND METHODS

Search method

The search for original documents was performed using two databases (S&WoS), in June 2023. The search was restricted to “article title, abstract, keyword” to exclude information unrelated to the topic.

For Scopus, the search equation used was TITLE-ABS-KEY (transplanting OR development AND transplanter OR design AND transplanter AND seedlings, AND automatic AND transplanter) AND (EXCLUDE(DOCTYPE , "re")) AND (EXCLUDE (DOCTYPE, "cr")) AND (EXCLUDE (DOCTYPE, "bk")), aiming to exclude books, review articles, and conference reviews. Meanwhile, for Web of Science, the search equation used was Topic (transplanting OR development AND transplanter OR design AND transplanter AND seedlings, AND automatic AND transplanter) AND (Agricultural Engineering). Additionally, a filter was applied to exclude articles unrelated to the topic and review articles.

Bibliometric analysis

The data obtained from S&WoS was in Bibtex format with complete records and cited references. Subsequently, in the RStudio software version 2022.07.2, the two databases were merged, and information from 12 duplicate records was removed. An Excel® file was generated with a total of 243 records. Bibliometric analysis was conducted using the Biblioshiny tool in the RStudio Bibliometrix software *(Aria & Cuccurullo, 2017)*. Fig. 1 shows the flowchart for data collection, analysis, and visualization.

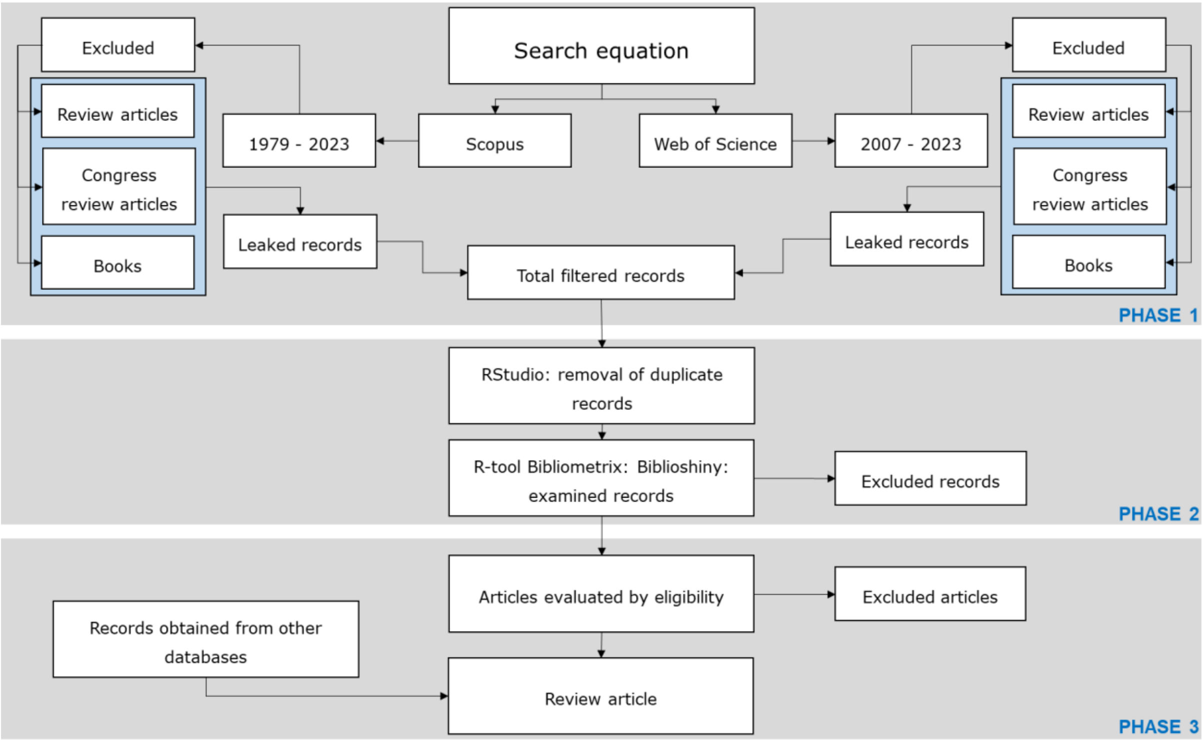

Fig. 1 – Flowchart for data search and analysis

Detailed review

In the detailed review, articles obtained from the bibliometric analysis were examined. Additionally, documents from sources beyond those used in this study were included, as they were not found in the initial S&WoS search (Fig. 1). The specific review was carried out based on the following variables in the design of equipment for automated seedling transplanting: physical and mechanical properties of seedlings, functional systems of prototypes, general characteristics, technical parameters, mechanisms and algorithms, current situation in Mexico, manufacturing costs, and areas of opportunity.

RESULTS AND DISCUSSION

The records analyzed (Table 1) were published between 1979 and 2023. A total of 243 records were analyzed, comprising 220 scientific articles and 23 conference papers.

Table 1

General information of the analyzed articles

Description	Results
Documents	243
Annual growth rate (%)	5.81
Document average age	6.63
Average citations per document	10.6
References	5128

Table 1
(continuation)

Description	Results
Documents	243
Keywords plus (ID)	1055
Author's Keywords	665
Authors	665
Authors of single-authored docs	10
Co-authors per document	4.69
International co-authorships (%)	3.292

Evolution of automated transplanting equipment

The first study related to automated transplanters was published in 1979, it refers to an automated feeder for transplanters developed by *Moden & Brewer, (1979)*. It wasn't until 1985 that the first automated transplanter for turf was recorded, achieving an efficiency of 97%. This prototype was developed by *Hauser, (1985)*.

The number of publications remained between zero and two articles per year for 28 years, totaling 13 articles. However, the boom in publications on automated transplanters began in 2008, reaching a total of five articles. This increase could be attributed to the global population growth and urbanization, leading to the need to enhance food production. For instance, by 2010, more than 50% of the population already lived in cities, and it is estimated that by 2050, two-thirds of the global population will reside in urban areas due to the migration from rural to urban areas in search of better opportunities *(Van Bavel, 2013)*. One consequence of this mobility is the increased demand for food in cities, but at the same time the labor force in the countryside decreases. This situation has driven the need to automate agricultural activities to boost productivity in the fields *(FAO, 2022)*.

The evolution of transplanters aligns with the advancement of automation and data processing algorithms that require significant computational power *(Tendulkar, 2014)*. However, the rise of dual-core processors, allowing simultaneous task management, for mass consumption began in 2005 by the Intel Corporation *(Intel, 2005)*. Additionally, the implementation of Artificial Intelligence (AI) as part of automation in agriculture necessitates Graphics Processing Unit (GPU) support for the neural networks used in machine learning by researchers in the last 12 years *(Xu et al., 2021)*.

The peak in study production occurred in 2021, with a total of 35 articles. Despite the challenges the world faced due to the adversities caused by the COVID-19 pandemic, it appears that authors took advantage of the isolation period to concentrate on developing and presenting their findings on automated transplanting. The evolution of article production over the years is presented in Fig. 2.

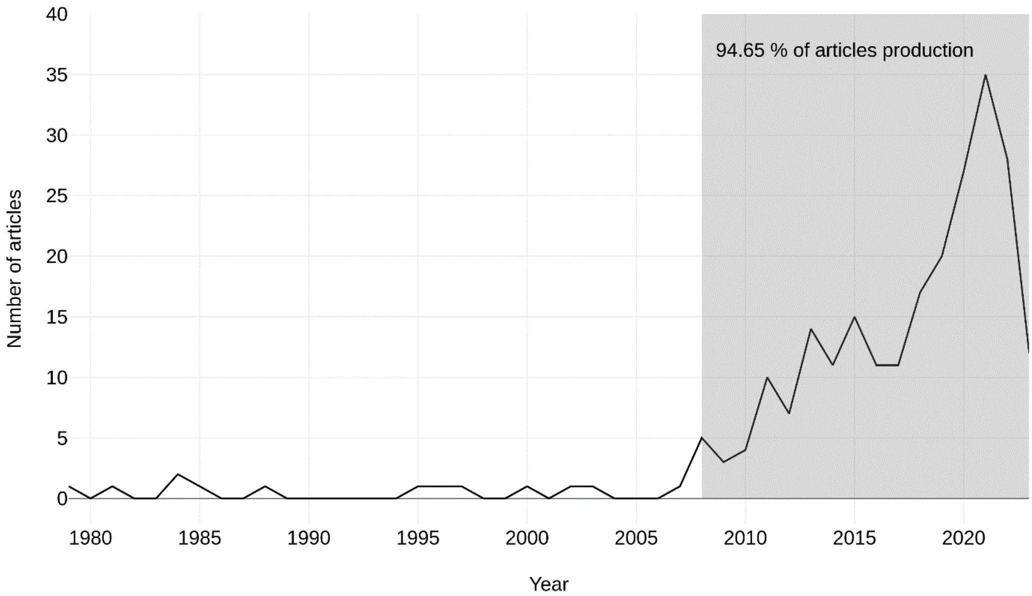

Fig. 2 – Origin and evolution of articles published between 1979 and 2023

Fig. 3 shows the 50 most frequently used keywords by the authors of the 243 analyzed documents. The term “*transplanter”* stands out as the most used, appearing in 14.4% of instances. “*Agricultural machinery”* follows with a 13.1% occurrence, and “*plug seedling”* is noted in 9% of cases. The term “*automated transplanter”* appears in only 4.1% of instances, ranking tenth in frequency. Fig. 3 shows the most used words regarding automated transplanting of vegetables.

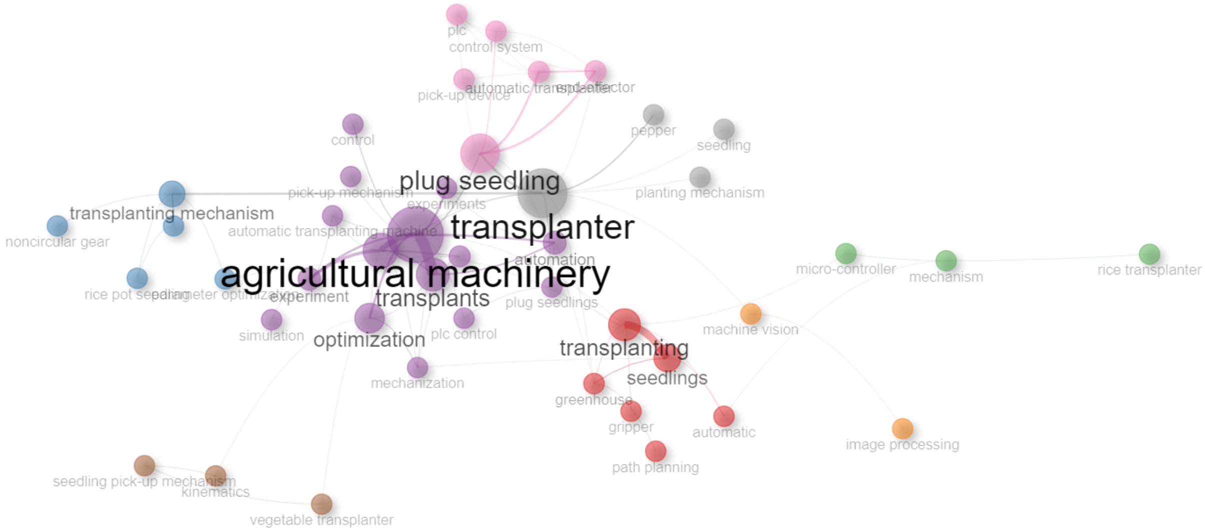

Fig. 3 – Co-occurrence network of authors' keywords

The evolution of automated transplanters is closely intertwined with technological advancements, as reflected in the keywords employed over the years. Notably, new terms such as *virtual simulation*”, “*machine vision*” and “*image processing*” have emerged, signaling the influence of AI and its technological innovations in automated vegetable transplanting.

Fig. 4 shows the terms used in articles related to automated transplanters from 1979 to 2023. The parameters considered include a minimum word frequency and the number of words per year, set at five and three, respectively. The term “*transplanter*” stands out with the highest frequency, serving as the commonly used general term to describe automated transplanting in these articles.

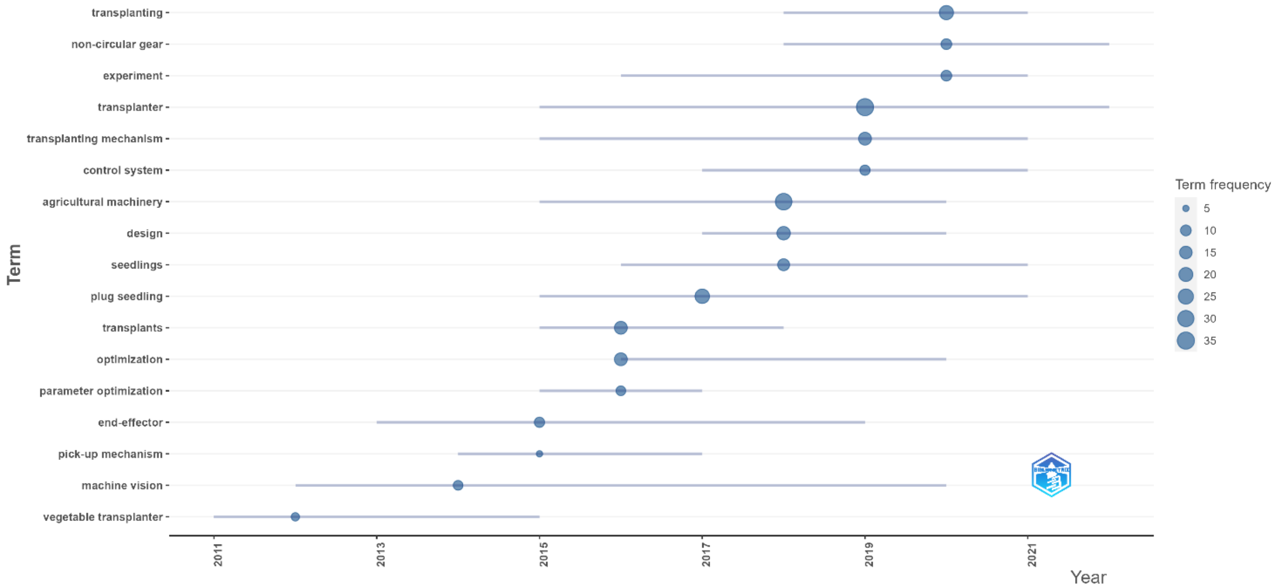

Fig. 4 – Current trends in automated transplanting-related topics

Scientific production on automated transplanters

The authors with the highest number of publications on the topic are as follows: in the first position, Hu J., Jin X., and Yu G., each with 18 published articles. The second position is held by Mao H., with a total of 17 published articles, and the third position is occupied by Han L., with 16 published articles.

The most cited authors are in the first position Kumar G. and Raheman H., each with a total of 10 citations. The second position is shared by Han L., Hu J., Kumi F., and Mao F., each with a total of seven citations, the third position is held by Ye B., with a total of five citations (Fig. 5).

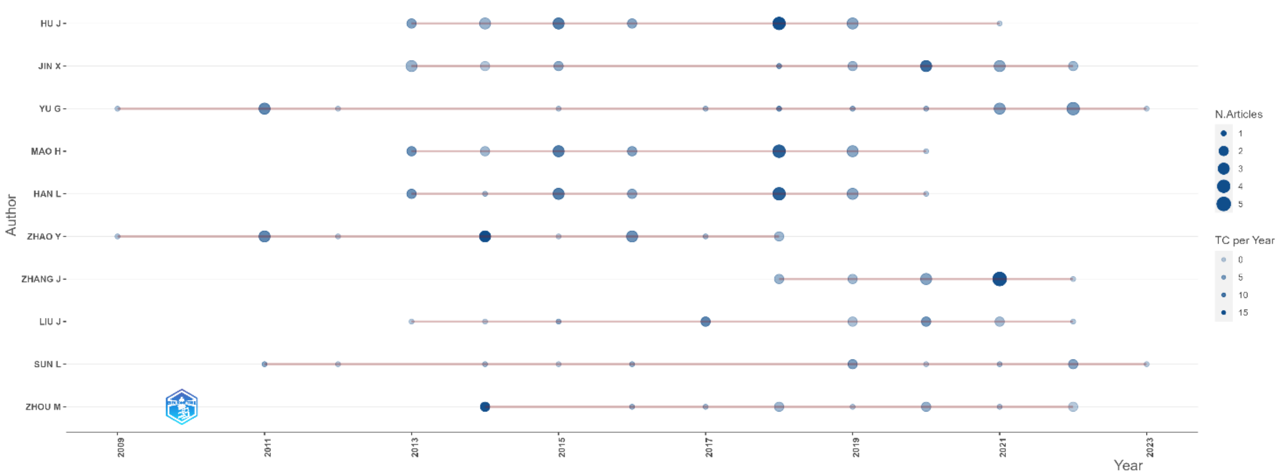

Fig. 5 – Authors' scientific production over time

The distribution of countries with the highest scientific production (Fig. 6) is indicated in blue. China, India, and the United States secure the top three positions. In the initial 28 years under analysis, the United States dominated scientific production. However, from 2007 onwards, India took the lead for six consecutive years. Yet, since 2013, China has been the leading country in scientific production on this topic. China has the highest number of citations (1645 citations), followed by India with 243 citations, and the United Kingdom in third place with 102 citations. The United States leads in collaborations, working with Spain, Bangladesh, and Korea, while China takes the second position, collaborating with Ghana and Japan. It's important to note that no information on this topic was found concerning Mexico.

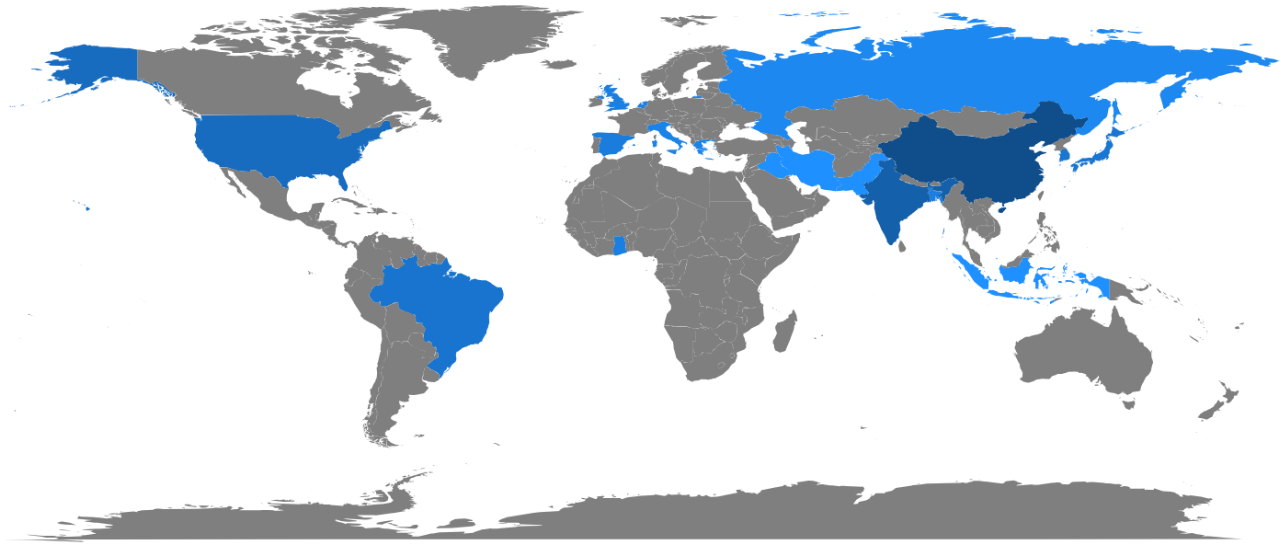

Fig. 6 – Leading countries in scientific production

Table 2 shows the most cited papers, these papers were published between 2008 and 2015, and the journals Nongye Jixie Xuebao/Transactions of the Chinese Society of Agricultural Machinery and Biosystems Engineering stand out, with the most cited articles worldwide. These documents present solutions for the process and automation of seedling transplanting.

Table 2

Most cited articles globally

Article	Authors	TC	TC/year	TC normalized
Mechanical within-row weed control for transplanted crops using computer vision	*(Tillett et al., 2008)*	102	6.38	2.90
Development of a walk-behind type hand tractor powered vegetable transplanter for paper pot seedlings	*(Kumar & Raheman, 2011)*	84	6.46	4.06
Co-robotic intra-row weed control system	*(Pérez-Ruíz et al., 2014)*	56	5.60	2.12
Design and test of automatic feed system for tray seedlings transplanter	*(Han et al., 2013)*	53	4.82	2.65
Kinematics modeling and parameters optimization of seedling pick-up mechanism of planetary gear train with eccentric gear and non-circular gear	*(Ye et al., 2011)*	51	3.92	2.46
Pincette-type end-effector using two fingers and four pins for picking up seedlings	*(Han et al., 2015)*	50	5.96	2.63
Design of automatic picking up seedling end-effector based on mechanical properties of plug seedlings	*(Han et al., 2013)*	42	3.82	2.10
Design and test of key parts on automatic transplanter for flower seedling	*(Feng et al., 2013)*	41	3.73	2.05
Development of single row automatic transplanting device for potted vegetable seedlings	*(Jin et al., 2018)*	38	6.33	2.76
Design of seedlings separation device with reciprocating movement seedling cups and its controlling system of the full-automatic plug seedling transplanter	*(Yang et al., 2018)*	37	5.14	2.22

TC– Total citations

Morphological and mechanical characteristics of seedlings

The design of any device or mechanism for an agricultural machine requires fundamental input parameters. Therefore, it is crucial to base it on the physical and mechanical characteristics of agricultural materials (*Mohsenin, 1986*). In the specific case of designing and evaluating an automated transplanter for seedlings *(Khadatkar et al., 2020)*, obtaining these parameters is essential to dimension the parts that make up the transplanting equipment. Not considering these variables would cause mechanical damage to the seedlings during transplanting and, subsequently, throughout the crop's development.

Khadatkar et al. (2021) used simulated seedlings for preliminary tests, replicating the ideal characteristics of pepper seedlings. In other words, homogeneous material was used to enhance efficiency in the prototype. Table 3 shows the physical and mechanical characteristics (seedling and root ball) used in the development and evaluation of transplanters designed by several authors.

Table 3

Characteristics of the studied seedlings and root ball

Species name	Physical and mechanical characteristics	Age (days) and #H	Substrate	Authors
Onion	-	-	-	*(Chowdhury et al., 2023)*
Chili	Height, weight, stem diameter, burst pressure, compression force and breaking force	30; 4-5	Coco peat, vermiculite and perlite (3:1:1)	*(Khadatkar et al., 2023)*
Chili	Height, canopy, moisture content and bulk density	28, 35 y 42; -	-	*(Chethan et al., 2022)*
Tomato and chili	-	30; -	-	*(Khadatkar et al., 2021)*

Species name	Physical and mechanical characteristics	Age (days) and #H	Substrate	Authors
Chili	-	-	-	*(Wen et al., 2021)*
Chili	Average stem diameter, height and weight	30; 4-5	Coco peat, vermiculite and perlite (3:1:1)	*(Khadatkar et al., 2021)*
Pepper	Height and root diameter	60; 6	-	*(Han et al., 2021)*
Cabbage	Height, failure resistance of the substrate and dimensions of the substrate	30; -	-	*(Cui et al., 2021)*
Pumpkin, pepper and tomato	Stem diameter, moisture content and pressure resistance/N	35, 30, 38; 3.5, 4.1, 5.6	-	*(Shao et al., 2021)*
Tomato	Stem height and diameter	-	-	*(Pérez-Ruiz & Slaughter, 2021)*

#H – Number of leaves

Due to the significance of the aforementioned characteristics, there are studies focused on determining specific values for these traits in a seedling based on its variety, as they are crucial for designing and evaluating automated transplanters (Table 4).

Table 4

Physical and mechanical properties studied in seedlings

Characteristics		Agricultural product (Variety)	Authors
Physical	**Mechanical**		
Age, mass, stem diameter, total height, canopy and moisture content	Impact test, stem and root ball compression test, and static friction coefficient	Chili (*Pusa Jwala*) and tomato (*Abhilash*)	*(Khadatkar et al., 2020)*
Age, height, mass, stem diameter and spreading diameter	Impact test, stem tension and compression test, and static friction angle and coefficient	Tomato (*Roma VF*)	*(Abubakar et al., 2020)*
Age, moisture content, number of leaves, height, stem diameter, mass, root ball and canopy density	Friction coefficient, stem and root ball compression test, and root ball penetration force	Tomato (*Ansal Hybrid* and *Seminis Company*), eggplant (*F1-Gaurav Hybrid* and *Pancha Ganga Seeds Company*) and cabbage (*Saint Hybrid* and *Seminis Company*)	*(Magar et al., 2023)*
Age, height of seedling and root ball, stem diameter, number of leaves, spread of leaves/millimeter and mass	Stem bending, tensile and compression test and stem clamping force until tray removal.	Bell pepper (*Xiaoxin No. 19*)	*(Shuangyan et al., 2022)*
Age, weight, bulb diameter, stem diameter, height and moisture content	Compression test and static friction coefficient	Onion (*Pusa Red*, *Set-126* and *Pusa Ridhi*)	*(Pandirwar et al., 2015)*

Obtaining the physical-mechanical parameters of each part of the seedling is crucial. Some authors focus on the stem, while others concentrate on the root ball (substrate characteristics), as demonstrated in the study conducted by *Han et al. (2013),* who conducted mechanical tests on the root balls of pumpkin seedlings. The following are the physical and mechanical characteristics to consider for the design of an automated seedling transplanter (Fig. 7). Some physical characteristics (as e, D, T) were derived from *Paneque et al., (2017),* and the remaining physical and mechanical characteristics were also used by the authors mentioned in Table 4.

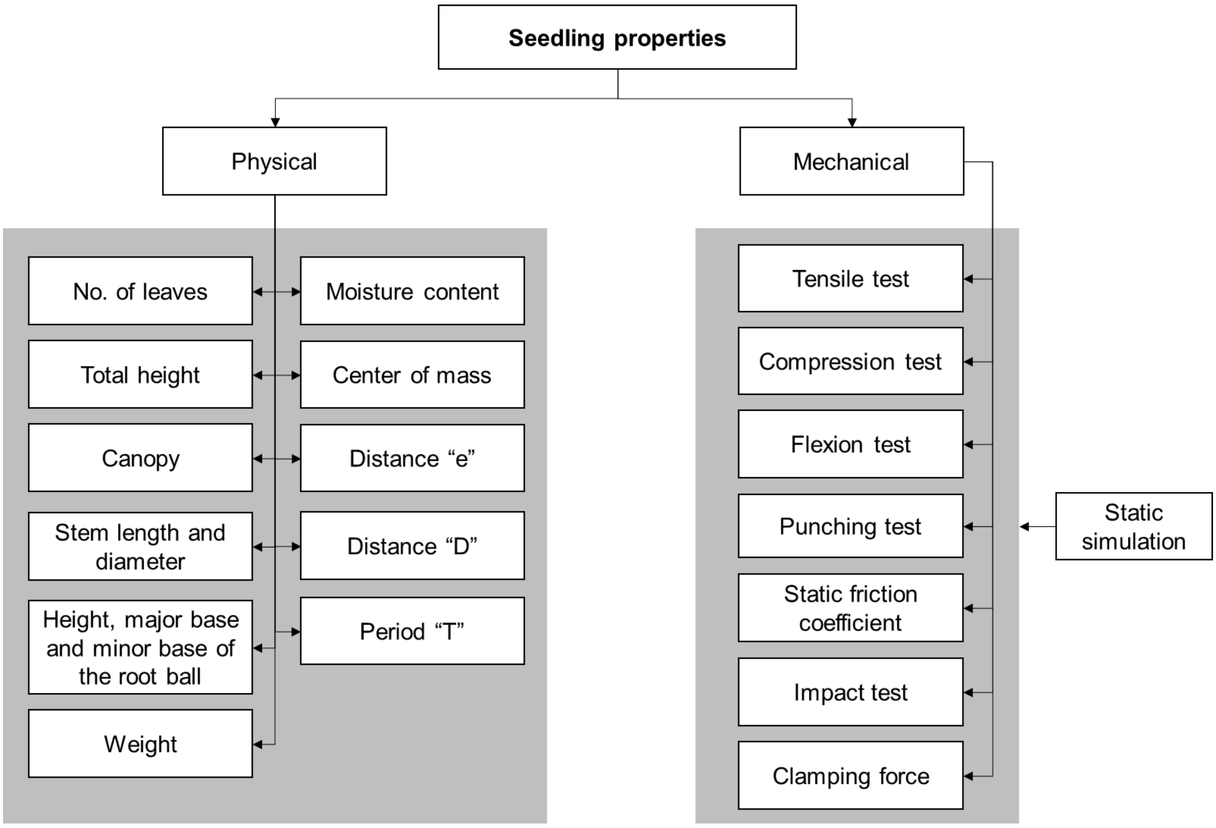

Fig. 7 – Physical and mechanical properties of seedlings included in the design and evaluation of an automated transplanter

Systems, features, and performance of transplanters

Fig. 8 shows the systems that comprise an automated transplanter. System one (Sis-1) covers the extraction of seedlings from germination trays, system two (Sis-2) handles the transportation of seedlings to the next system, and system three (Sis-3) has the function of seedling transplanting. The subfunctions of the transplanter are shown in white boxes. As with any automated machine, there are input power and input signals; on the other hand, there are output power and output signals.

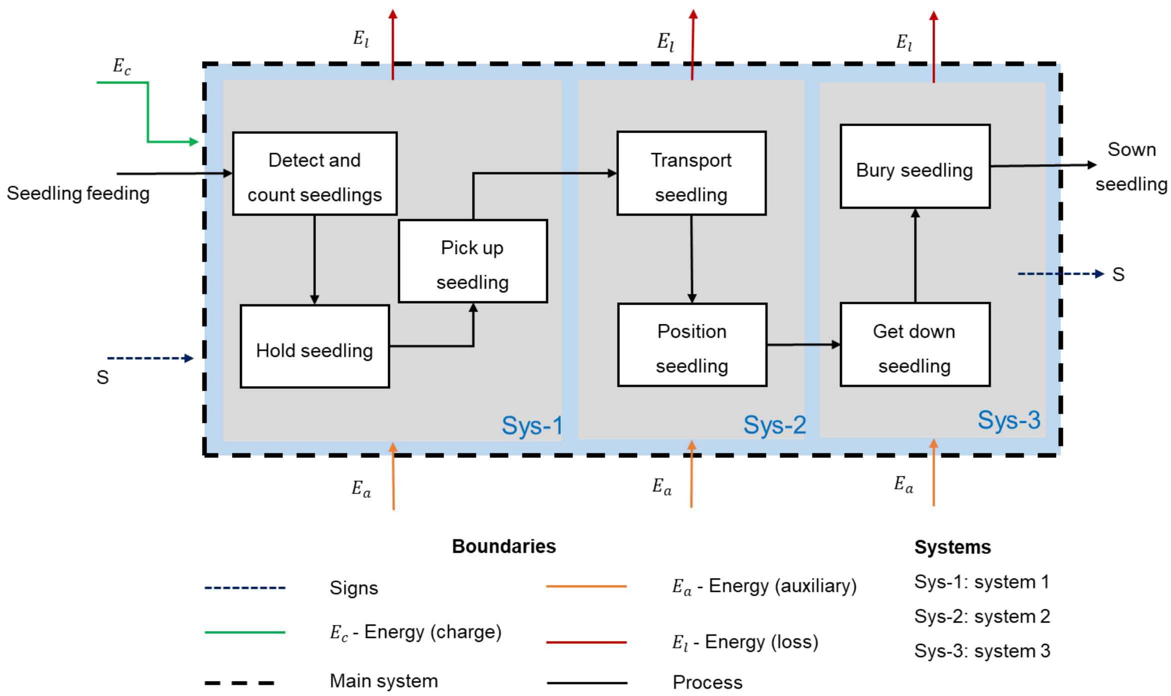

Fig. 8 – Sub-functions of a machine for automated vegetable transplanting

Table 5 shows the systems used by some authors in their research, revealing three general systems that a transplanting machine comprises. It is important to mention that all the studies shown in the table used plastic trays for germination due to their flexibility and durability, in contrast to polystyrene trays, which are more fragile and prone to break.

Table 5

Transplanter components

Seedling feeding	Extraction system (mechanism)	Transport system	Transplant system	Authors
Black plastic tray	Automatic	Automatic	Mechanic	*(Chowdhury et al., 2023)*
Black plastic tray	Manipulator with effector	Manipulator with effector	Manipulator with effector	*(Khadatkar et al., 2023)*
Black plastic tray	Manual	Gravity fall	Automatic	*(Chethan et al., 2022)*
Black plastic tray	Conveyor belt	Hopper	Automatic	*(Khadatkar et al., 2021)*
Black plastic tray	Extractor cylinder	Dosing plate automatic	Automatic	*(Wen et al., 2021)*
Black plastic tray	Spinning fingers	Metering shaft automatic	Automatic electromechanical system	*(Khadatkar et al., 2021)*
Black plastic tray	Automatic collection system		Basket type planting (Automatic)	*(Han et al., 2021)*
Black plastic tray	Conveyor belt and automatic device (mechanical arm)	Mechanical buckets	Automatic	*(Cui et al., 2021)*
Black plastic tray	Effector	Automatic chain cups	Automatic	*(Shao et al., 2021)*
Black plastic tray	Manual	Drum with 5 fingers (one seedling/finger)	Automatic	*(Pérez-Ruiz & Slaughter, 2021)*

There are several working environments in vegetable production, for example, open field with or without mulch, greenhouses with or without mulch, and greenhouses with pots. Each transplanter designed will always be focused on one or two working environments, depending on the region, production volumes and level of technology. Likewise, they have advantages and disadvantages, both in terms of production and profits. Furthermore, depending on the working environment, dimensions, weight, productivity and performance of the prototype are defined. Table 6 shows the characteristics of some transplanters developed with different working capacities.

Table 6

Properties of transplanters

Dimensions (l x w x h (mm))	Weight (kg)	NR	Work environment	Authors
875 x 1626 x 2036	690	6	Open field	*(Chowdhury et al., 2023)*
630 x 510 x 120	-	1	Open field	*(Khadatkar et al., 2023)*
940 x 680 x 890	-	1	Open field (with and without mulch)	*(Chethan et al., 2022)*
-	-	2	Open field (without mulch)	*(Khadatkar et al., 2021)*
2400 x 2200 x 1900	774	2	Open field (without mulch)	*(Wen et al., 2021)*
2030 x 1295 x 1015	210	2	Open field (laboratory experiment)	*(Khadatkar et al., 2021)*
-	-	2	Open field (without mulch)	*(Han et al., 2021)*

Dimensions (l x w x h (mm))	Weight (kg)	NR	Work environment	Authors
3100 x 3000 x 1600	-	4	Open field (without mulch)	*(Cui et al., 2021)*
-	-	-	Experimental in laboratory	*(Shao et al., 2021)*
-	-	3	Open field (without mulch)	*(Pérez-Ruiz & Slaughter, 2021)*

l- large, w- width, h- height, NR– number of rows

When testing and evaluating an automated transplanter, technical parameters such as speed and transplanting capacity are considered to determine if the prototype is efficient according to its intended working environment. These parameters, along with the number of seedlings successfully transplanted, serve as a benchmark for transplanting efficiency during a workday. Achieving a 100% success rate is challenging due to the influence of independent variables such as weight, shape, and physical dimensions of seedlings, which are inherently non-uniform. Moreover, they are susceptible to mechanical damage during extraction from germination trays, handling, and transplanting. Consequently, there is always a percentage of failure in the process. Table 7 outlines the technical parameters used in both the design and evaluation of the analyzed prototypes.

Table 7

Technical parameters of transplanters

Transplant speed (m/s)	Transplanting capacity	Successful transplant (%)	Failure (%)	Authors
0.24	-	-	-	*(Chowdhury et al., 2023)*
-	3 SG/min	90.3	7.6	*(Khadatkar et al., 2023)*
0.117-0.156	15 SG/min	-	-	*(Chethan et al., 2022)*
-	10.35 SG/min	90-92.6	4.5-5	*(Khadatkar et al., 2021)*
-	80 SG/(min*row)	92.08	3.61	*(Wen et al., 2021)*
0.556	-	90.3	2.1	*(Khadatkar et al., 2021)*
-	120 SG/min	97.5	3	*(Han et al., 2021)*
0.306	55 SG/min	93.31	3.42	*(Cui et al., 2021)*
-	6-12 SG/min	73.33-88	1-8.57	*(Shao et al., 2021)*
0.222 y 0.444	-	90	-	*(Pérez-Ruiz & Slaughter, 2021)*

SG – seedlings

There are machines designed for transplanting in greenhouses. *Hu et al., (2016)* developed and tested an automated transplanter for greenhouses, achieving a transplant success rate of 90.23%, a capacity of 120 seedlings per minute, and a planting precision within the range of 0.15-1.22 mm.

Manufacturing and operating costs

The cost of production and the selling price are features to consider in the development of automated transplanters; therefore, it is important and necessary to analyze both fixed and variable costs to justify the final cost of the prototype. It is also essential to compare the costs of manual transplanting against the costs of transplanting using an automated transplanter to determine if the prototype indeed reduces the cost of the transplanting phase.

In the analyzed works, only a few authors report the cost of their prototype. Of the total prototypes and mechanisms analyzed, 97.5% do not report the costs of the components used since they are more focused on research than on production. *Chethan et al., (2022)* mentioned that the prototype they developed does not require electricity and was constructed with locally available, inexpensive materials. They considered their prototype to be semi-automated and cost-effective.

When comparing transplanting capacities between automated and manual methods, the study found, according to *Khadatkar et al., (2021)*, that the average manual transplanting rate ranges from 2.5 to 4.5 seedlings per minute per person. Except for the prototype developed by *Khadatkar et al., (2023),* whose capacity falls within the range of manual transplanting capacity, the prototypes presented by the authors listed in Table 6 surpass traditional capacities by more than 100%. In economic terms, as reported by *Khadatkar et al., (2021)*, there was a 30.55% cost reduction in mechanically transplanting tomatoes compared to manual operations. For pepper crops, a decrease of 6.39% was observed. Therefore, it is inferred that transplanting costs will consistently be lower in a mechanical process.

Functional systems in automated transplanters

Several studies focus on one or two systems, or the development of an innovative mechanism used in transplanters. Regardless of the number of systems, their efficiency is determined by evaluating the success rate of transplanting. It is also crucial to evaluate the percentage of seedlings that remain upright, as this significantly contributes to their survival. Some of these studies include:

Hu et al., (2022) developed an integrated automated transplanting mechanism for the collection and transplantation of pepper seedlings in trays with holes. The 3D model was designed using SolidWorks, and its dynamic trajectory was modeled in Matlab. They achieved a seedling selection success rate exceeding 91.1%, a planting success rate of 78.5%, a seedling erection rate of 94.9%, and a coefficient of variation in plant spacing below 14.1%. These results demonstrated its suitability for real-field transplanting.

The pressure applied during seedling gripping poses a challenge, as it can lead to issues such as tissue damage in the stems or root ball. For this reason, various authors have developed different types of grippers. *Li et al., (2022)* designed and tested a gripper (Force Feedback) for picking up seedlings in an automated transplanter. This gripper is based on the linear Hall element. The gripping force detection system exhibited a sensitivity of 0.0693 V/N, linearity of 3.21%, a medium coefficient of determination of 0.986, and a range of 10 N. It met the requirements for gripping force during transplanting, being stable and adaptable to seedlings.

Zhou et al., (2020) developed a mechanism with a punching device for transplanting cayenne pepper seedlings into pots. The results obtained showed that the specific trajectory and transplanting mechanism met the required transplanting standards, and the success rate of seedling collection was 92.4%, confirming the correctness and feasibility of the transplanting mechanism.

On the other hand, *Chen et al., (2023)* designed a mechanism to pick up seedlings from an ejector belt, it was based on the discrete element method by using EDEM simulation software. They conducted substrate studies to determine the best variant of the proposed designs and found that when using the optimal combination of working parameters for seedling collection, they achieved a qualified seedling rate exceeding 90%, with a clod fragmentation rate of less than 20%. The seedling extraction system is effective for a transplanter in dry soil.

Modeling vegetables is a complex task that requires high computational resources. *Francis et al., (2014)* carried out a study to mathematically model the behavior of vegetables when extracting them from the root, using the Godwin and O'Dogherty equation for soil penetration tools as a foundation. They initially performed experiments with strain gauges to understand the force-time relationship of the device, indicating an initial force value of 1.1319 N. In the model under similar conditions, the force was determined to be 1.1389 N. They concluded that with this research, it is possible to optimize and design seedling collection devices for transplanting.

It is essential to consider the mechanical damage suffered by seedlings; typically, the stems and the root ball are the most affected, affecting production. *Wen et al., (2021)* reported that in the test conducted on their prototype, only 0.28% of the total used seedlings were damaged. This is considered very acceptable, as at large scales, there are minimal losses in seedlings and production costs. For instance, out of 1000 seedlings, only 3 of them are lost.

In recent years, part of the design of transplantation machines has been focused on strategies that help to optimize transplantation times. Consequently, several authors have developed algorithms to address this issue, and some of them are mentioned below. *Tong et al., (2022)* optimized the transplanting route of seedlings with multi-end effectors using an enhanced algorithm. The average calculation times they obtained for the common sequence method (CSM), greedy algorithm (GRA), greedy genetic algorithm (GGA), and improved greedy simulated annealing algorithm (IGSA) were 0.002, 0.007, 6.94, and 3.49 seconds in MATLAB

(R2019a), respectively. They commented that these algorithms can meet real-time operation requirements except for GGA. This research can be adapted to accommodate new numbers and arrangements of effectors.

He et al., (2022) designed and tested a control system for a sweet potato feeding and planting device, which consists of a pre-treatment seedling conveyor belt. According to the results obtained in the test, the average error of the seedling feeding motor speed was 4.04%, and for the planting motor speed was 3.28%. The lowest coefficient of variation (7.42%) in seedling spacing was achieved during tests at a low speed. They concluded that the system meets the control requirements for the automated seedling feeding and planting device in transplanting.

Furthermore, *Jin et al., (2021)* employed Kinect visual processing to obtain and process information about seedling height and leaf edge. They established and applied the working coordinate system of transplanting manipulator in route planning to avoid obstacles. Combining this with the inclined manipulator, they proposed the obstacle avoidance transplanting method. With this manipulator, they achieved a 4.70% leaf damage rate, a 16.67% stem bending rate, an 83.45% substrate integrity, and an 87.36% transplant quality. The transplanting time for a seedling was 8.32 seconds. The authors ensure the reduction of damage to the seedlings.

On the other hand, *Li et al., (2022)* optimized the transplant route in seedling germination trays using the improved A* algorithm for replanting. This algorithm reduced the time by 10.15 seconds compared to the Common Sequence Method (CSM) for each seedling tray. It was used to replant the cavities where the seedlings did not germinate or were defective with healthy seedlings. Additionally, it can be used for transplant route planning.

Current situation on prototype development in Mexico

In Mexico, the equipment developed for automated transplanting is scarce, with most machines being imported. However, in the course of the present research, a prototype developed in Mexico was identified. *Gutiérrez et al. (2009)* designed and built a transplanting mechanism (module) as the main component of a bare-root strawberry seedling transplanter on mulched soil. The operating principle is based on a module that remains in contact with the soil for a determined period. It features mechanisms for plastic cutting (including hiding it) and automated plant insertion into the soil. The plastic cutting had a 100% success rate; the plastic concealing activity had an efficiency of 95%; the success rate for plant placement with tweezers was 95%, and the efficiency in the verticality of the seedlings was 85%.

There is a limited amount of technology and information available on automated vegetable transplanting equipment in Mexico, although there is evidence of research work that has not been formally published. The equipment currently sold and used in the country is designed for different working conditions and focused on large growers. Therefore, there is an area of study that should be addressed, since there is a need for equipment with specifications suitable for small and medium-sized growers, who represent the majority, but have fewer possibilities of accessing automation technology because of the cost and capability.

Areas of opportunity for future research

Liu et al., (2021) conducted a design for a sweet potato transplanter based on a robotic arm. They found that the adjustment of the arm is complex as it cannot adapt to all planting terrains, negatively impacting the crop quality on ridges. Additionally, the target detection algorithm heavily relies on the quantity and quality of training images. When the transplanting environment changes, such as from a sunny day to a cloudy day, the detection results are affected. While the transplanter achieves various sweet potato transplanting methods, the single-ridge operation mode limits the efficiency of the transplanting process.

Tong et al., (2022) conducted research on optimizing the transplanting route of seedlings with multi-end effectors using the Improved Greedy Simulated Annealing (IGSA) algorithm. They proposed that, to enhance transplanting efficiency, increasing the number of end effectors would be beneficial, particularly when performing transplanting operations in dense seedling trays.

Meanwhile, *Shao et al., (2021)* developed a multi-adaptive feeding device for automated seedling plugs for a multi-seedling transplanter with six grippers. They noted that the success rate needs further improvement to meet the practical application of high-speed transplantation. They also commented that as future research, the automated feeding device could be manufactured by professionals to achieve high precision and stability.

In agriculture, the germination percentage is not 100% due to different situations such as seed quality, temperature conditions, seedbed humidity, etc. Therefore, if there were tray cavities without seedlings, the transplanting process would not be 100% complete in the furrows.

On the other hand, *Hu et al., (2022)* found issues related to the rotation speed of the mechanism they designed, as it generated vibrations that affected the transplant quality. They recommended further research into mechanisms to avoid generating vibrations when placing the plant on the ground and keeping it in a vertical position.

Paradkar et al., (2021) developed a dosing mechanism consisting of a serial robotic arm for handling seedlings in paper pots using a vegetable transplanter. They mentioned that the sources of reduced efficiencies from the ideal (100%) were due to inclinations caused by seedling transport due to friction and the operating speed of the conveyor and the damage occurred to the seedlings due to the robot arm's higher gripping force. Therefore, studying the physical-mechanical properties of seedlings is crucial for later use in the design of mechanisms used for transplanting.

Yongwei et al., (2018) recommended that, when designing the final gripper, it is crucial to consider the cultural practices specific to vegetable seedlings in the country where the mechanism will be utilized.

For the design of an automated transplanter, it's essential to define its parameters as no single machine adapts to all work scenarios. Therefore, it should be considered the cultural practices of the country, region, and the targeted type of growers, soil conditions, climate, type of germination tray, and the seedbed where the seedlings are produced. This approach aims to achieve germination rates exceeding 95% in trays, thereby optimizing the trajectories of the seedling extraction mechanism. Furthermore, the design should be accessible to small growers. Currently, most of the existing transplanters are designed for growers with large cultivation areas.

CONCLUSIONS

Automated transplanters have become very important in vegetable production because they reduce time, labor and, therefore, costs by up to 31% compared to manual transplanting; however, although this technology is expensive when developing a new prototype, it is essential not to disregard the limited availability of labor and the associated costs. Moreover, uncertainties in the quality of field operations performed by agricultural workers should be considered. Therefore, automation proves to be a favorable alternative.

The bibliometric analysis and detailed review indicate that technological progress on automated transplanters have evolved with the help of computational development. Researchers have created new prototypes for different crops, considering the conditions of their countries. However, there was limited progress in automatic transplanting (a total of 13 articles related to the topic) over 28 years, experiencing a surge in 2008 and a substantial increase in 2021 with a total of 35 published articles. Nowadays, databases of scientific articles across all fields, including automatic transplanting, are updated daily, in contrast to the previous practice of annual updates until 2007.

Several critical variables must be considered when designing an automated transplanter, such as physical and mechanical properties of seedlings. These parameters are essential for sizing and calculating the characteristics of the machine's components, ensuring they align with the intended functionality and preventing potential mechanical damage. It is also essential to test and evaluate the developed prototypes to determine the working speed, quantity of seedlings transplanted within a specified timeframe, efficiency, and percentage of failure during transplanting. Furthermore, it's important to consider the costs associated with the design, analysis, and construction time of the prototype.

Technological progress plays a pivotal role in the advancement of diverse sectors, notably in agriculture for food production and its broader economic impact. In the specific case of Mexico, it is necessary to take up the advances achieved so far in this area and develop prototypes for the automated vegetable transplanter, aligning with the unique conditions and characteristics of the country. By doing so, these transplanters can become valuable tools for small and medium-sized growers, aiding in cost reduction and integrating technology akin to that used by larger growers. This approach not only fosters competitiveness with potential producing countries and may even contribute to achieving food sovereignty.

This review article aims to show the scientific community the evolution and technological development of automatic transplanters, as well as the importance and impact of the development of technology to improve the quality, time and costs of vegetable transplanting. Limitations of this review on the development and evolution of automatic transplanters include possible study selection biases that might favor certain types of technologies or outcomes, lack of comparative studies evaluating different transplanters under various conditions, difficulties in generalizing findings due to variability of settings and technologies, possible conflicts of interest on the part of the authors reviewed, scarcity of data on long-term performance, environmental impact, potential conflicts of interest on the part of the authors analyzed, scarcity of data on long-term performance, environmental impact, lack of long-term follow-up on durability and total cost of transplanters, as well as limitations in access to the literature that could lead to a partial view of the available evidence.

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