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Evaluation of an automatic tomato plant pollinator in a field assessment

Colaboración
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RESUMEN: La polinización suplementaria en la planta de tomate permite obtener frutos más grandes con mayor calidad. Los sistemas de polinización tradicionales pueden ser manuales, abejorros, polinizadores eléctricos y sopladores. Todos ellos aumentan la inversión de producción en el cultivo. El objetivo de este estudio fue evaluar si la polinización automática (AP) podría ser útil para polinizar las plantas de tomate bajo invernadero. Se realizó una prueba de campo para analizar la actividad como polinizador de la planta de tomate versus la polinización manual (MP). Se realizó un diseño experimental con dos grupos, utilizando muestras independientes de igual tamaño, donde 20 plantas fueron completamente aleatorizadas y numeradas para cada uno de los tratamientos. Los resultados mostraron 25 °C como una excelente temperatura de polinización. En los primeros 150 días, AP polinizó el 90% de las flores frente al 75% de las MP. Tanto la producción de tomate como los racimos por planta fue más elevada con el AP, con un total de 963 (48.2 ± 14.6) tomates versus 714 (35.7 ± 16.7) (p <0.05) y 130 (6.5 ± 1.6) vs. 108 (5.4 ± 1.5) (p <0.05) clústeres por planta Los resultados demuestran la viabilidad de usar un robot para polinizar tomates bajo invernadero durante una temporada completa.

PALABRAS CLAVE: Automation; computer applications; crop monitoring; monitoring robots; sensor.

ABSTRACT: Supplementary pollination in tomato plant allows to obtain larger fruits with higher quality. Traditional pollination systems can be handheld, bumblebee, electric pollinator, and blower. All of them increase production investment in the crop. The objective of this study was to evaluate whether automatic pollination (AP) could be useful to pollinate greenhouse tomato plants. A field assessment was carried out to analyze the activity as pollinator of the tomato plant versus manual pollination (PM). An experimental design with two groups was carried out using independent samples of equal size, where 20 plants were completely randomized and numbered for each of the treatments. The results showed at 25 °C as an excellent pollination temperature. In the first 150 days, AP pollinated 90% of the flowers compared to 75% of the PM. Both tomato production and clusters per plant were higher with the PA, with a total of 963 (48.2 ± 14.6) tomatoes versus 714 (35.7 ± 16.7) (p <0.05) and 130 (6.5 ± 1.6) vs. 108 (5.4 ± 1.5) (p <0.05) clusters per plant. The results show the feasibility of using a robot to pollinate tomatoes under a greenhouse during a complete season.

KEYWORDS: Automation; computer applications; crop monitoring; monitoring robots; sensor.

INTRODUCTION

Most of the cultivated plants depend on pollination to produce their fruits. On nature, this process is carried out by insects, birds or mammals [1]. Among the factors that reduce productivity and quality of tomato crop are as follows: lack of pollination, unfavorable temperatures for anthesis, insufficient lighting, excess or lack of nutrients, and relative humidity [2]. The major crops in Mexico that require pollinators are beans (Phaseolus vulgaris L.), peppers (Capsicum annuum L.) and tomato (Solanum lycopersicum L.) [3].

In the last years, the cultivated area under greenhouse conditions has grown to more than half of this area (70%) focused most on tomato (Solanum lycopersicum) [4]. This scenario have motivated their development and also increased the demand for supplementary pollination to obtain larger fruits for a higher yield and more commercially attractive fruits. Different methods such as the use of manual vibration, wind shaking and pollinating insects have been used until now in low-tech greenhouses.

Greenhouse tomatoes require supplemental pollination during anthesis and are usually pollinated by manual vibration, which is a very arduous and expensive task. In Europe, insect colonies (Bombus terrestris L.) have been used since 1987 to pollinate greenhouse tomato plants, replacing manual pollination [5]. Although the use of bumblebees as greenhouse pollinators was rapidly disseminated, very little research was carried out regarding problems with bumblebees, for example, pesticides such as stressors [6].

Robotics in agriculture is not a new technology, since its use has a history of more than 30 years. Its worldwide utilization has increased joint with the capacity of Hi-Tech computers, technology research and automation. As the world population is expected to increase to nine billion by 2042, which means that there will be a considerable challenge in the provision of high quality food for this population. Furthermore, the labor force in agriculture is declining and automation technology is emerging to replace some traditional labor [7]. For example, in the production of special crops, labor is often tedious, non-ergonomic and performed by unskilled personnel. Automation technology improves productivity, health and staff satisfaction. However, there are serious technical challenges regarding the automation of operations and the control of dynamic processes. A recent robot, which is the closest to commercialization, is a strawberry harvester robot [8], but is still in the exploration phase.

According to Vega-González [9], the construction of a prototype consists of four phases, which are called bench prototype, concept prototype, laboratory prototype and technological product. Just a few robots can reach the last phase and the most of the cases due to the great amount of investment necessary for producing the prototype in industrial scale.

On the other hand it worth to mention that floral anthesis starts early in the morning around 6 am and the flower continues opening until 11 am. The peak period of anther dehiscence is between 8 to 11 am depending upon the initiation of sunshine, atmospheric temperature and humidity. At temperatures ranging between 18 to 25 °C, the pollen remains viable for 2 to 5 days, the stigma becomes receptive 16 to 18 h before anthesis and retains the receptivity up to 6 days after anthesis, i.e., shortly before the flower withers. This long duration of stigma receptivity from near one day prior to 6 days after anthesis, permits controlled pollinations. These are further facilitated by the long-duration viability of pollen as the pollen retains its viability for 2 to 5 days at temperature ranging from 18 to 25 °C [10].

Given these concerns, the aim of this study was to evaluate whether the automatic pollination (AP) could be useful to pollinate tomato plants under greenhouse conditions according to the setup parameters.

MATERIAL AND METHODS

Design and construction of the automatic pollinator

The robot (AP) includes a DHT11 sensor (Aosong Electronics Co., LTD., China) and the vibration system, both devices were connected to an Arduino board. The AP is a dynamic open-loop control robot, which was developed using an embedded system [11], to record and determine the appropriate stage when the electric motor must be turn on/off. Furthermore, the robot consists in one horse power motor (DC motor electric 12 volt 56C 1800 rpm, PTJ Industrial) capable to vibrate in an eccentric way and a digital recording system that stores the information in a micro SD memory configured to acquire greenhouse data. The operation of the AP was evaluated by counting the working hours, recording variables (temperature and relative humidity), switching the on/off system and vibration according to the set point parameters, which were controlled by LabView 2013 (National Instruments).

Study area

This research was carried out from January 1st to July 15th 2016, in the Technological Institute of Tamazula, located in the city of Tamazula de Gordiano, Jalisco, Mexico. Tomato plants (Solanum lycopersicum L.) were planted with a density of 3.2 plants m-2 in a plastic greenhouse, with a traditional design. The greenhouse is a 4-connected gutter (numbered 1-4). The pollination was carried out in the gutter 1 and 4 for the MP and AP, respectively. To establish climate, irrigation, fertilization, tutoring and pest control and other cultural labors, the practices suggested by Jaramillo [2], were followed.

Robot functionality and activation

Two treatments were evaluated as follows: i) flower pollination through AP, and ii) flower pollination through MP. In order to evaluate the effect of the pollination system, the number of tomatoes and clusters per plant was quantified. The MP was performed every day by the same person; simultaneously, the AP was carried out in its respective section by the robot according on the activation parameters the set point was established at 25 ± 0.9°C. The treatments were established in two different gutters as above mentioned (Figure 1A). Twenty plants were randomly selected and numbered (1-20) for each section either for the MP or AP.

Data analysis

In order to evaluate the feasibility to automatically pollinate tomatoes under greenhouse the AP activity was compared versus MP. Dataset were analyzed using the independent samples t- test. To identify significant difference among treatments and statistical significance for all comparisons was made at $p<0.05$. Data are shown as the mean SD. To evaluate the effect on the treatment along the days a Pearson correlation was performed.

RESULTS

The development of a prototype consists in four phases. In the first stage (D0 to D1), the construction of a preliminary device or bank prototype is started, which serves to carry out the initial assessment for the technological improvements, between stages D1 to D2 improvements are made to the bank prototype until it reaches a concept prototype from which a technical and functional feasibility validation of the device is achieved.

Our robot is in stage D2, where the improvements were made to the bank prototype until it reached a concept prototype through system validation, and technical-functional device feasibility. The robot was located in the upper part of the gutter 4 (Figure 1B). The robot works by means of the eccentric motor movement which is located at the upper of the gutter 4 and interlaced with the main tutor, the movement of the robot vibrates both the main tutoring and vertical tutoring, which leads to flower pollination.

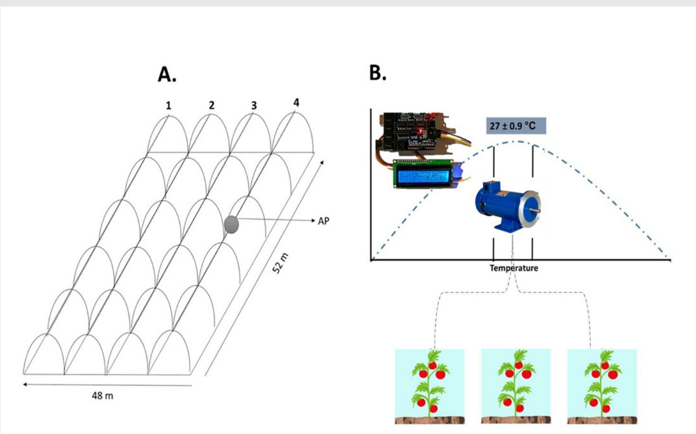

Figure 1. Greenhouse divisions and location of the automatic pollinator. A. Greenhouse area (52 m long -48 m wide, divided into 4 gutters (1-4).) B. Automatic pollinator (located in the upper of the gutter 4).

This robot (AP) has been designed to perform the task of replacing either bumblebees or manual pollination due to these two methods are costly. On the other hand, bumblebees have an initial cost of $800 USD per hectare (ha), with subsequent expenditures of $250 USD every 22 days ha-1 for 6 months, which has a final total of $2300 USD. In this study, showed how a single AP activation could pollinate at least of the greenhouse. However, according to a preliminary test a 1/3 of greenhouse pollination were performed (Data not shown). Conversely, during manual tomato pollination at least, two people per day per hectare is used, with an approximate time of one hour per person. In addition, an approximate cost of $35 USD per day (three days long) with a total of $2457 USD during six months is spent, in which that time is only occupied to pollination labors (Figure 2). Hence, with three robots is sufficient to pollinate one hectare under greenhouse conditions, the final cost for each ha was $150 USD ($450 USD in three robots) which means at least 5.1 and 5.4 times cheaper than Bumblebees or MP, respectively.

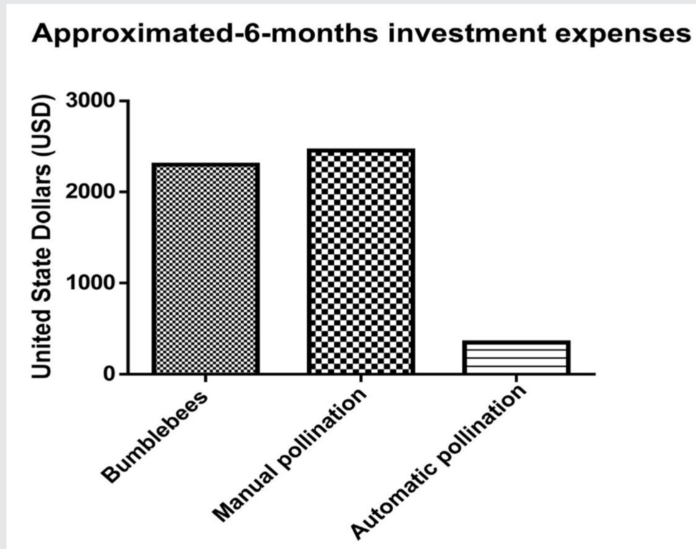

Figure 2. Six-months total expenses during greenhouse pollination.

Another variable considered in this study was the relative humidity which was correlated with temperature, since the relative humidity values were higher than 80%, can stimulates the plant diseases development and difficult the fertilization by pollen compaction. On the other hand, the low percentages of relative humidity cause difficulties in the pollen fixation to flower stigma. The AP vibrated in the programing parameters and was capable to work with different set points either for temperature or relative humidity (Figure 3). In addition, we can observe that the 25 °C setup parameter was reached at least two times in one day.

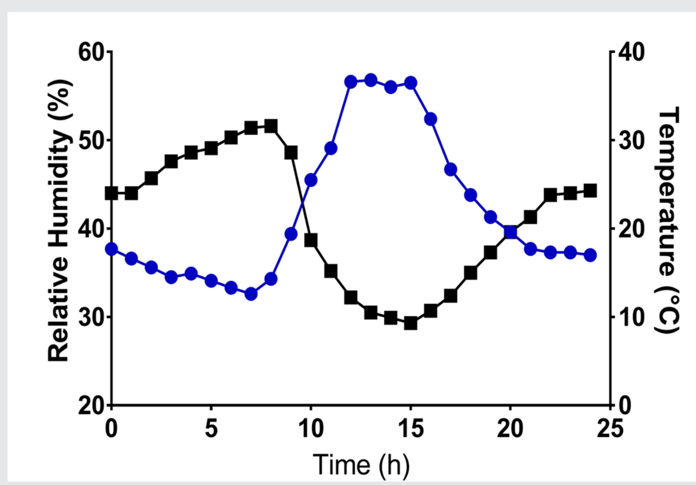

Figure 3. Temperature (blue circles) and relative humidity (black rectangles) recording. The greenhouse data acquisition was stored in a micro SD memory for the further analysis.

To verify whether the robot could detect temperature and relative humidity and simultaneously could be activated in an automatic way and also perform the vibration, the activity of the robot was recorded for six months (January-July). Figure 4A, shows the temperature kinetics in three consecutive days, as we can see the min-max temperature ranges from 10 to 37 °C, and every day at least two activations could be reached one for the morning at 9:45 am and four hours later at 13:46 pm and the vibration was performed only when the greenhouse reached the set point parameter (25 ± 0.9 °C), all the measures were corroborated with external instruments (data not shown).

Figure 4B, shows the temperature inside the greenhouse with a minimum and maximum temperature range oscillating between 12°C and 42°C during all the studied variables measurement. This was an extra point to our robot due to this robot could be activated not only in determinant temperature but also in determinant humidity inside the greenhouse and therefore, could perform several activations. Moreover, the robot has the ability to store great amounts of data (depending on the storing devices), and the performing and activation of the AP is very precise and did not require any previous or constant calibration during all the study.

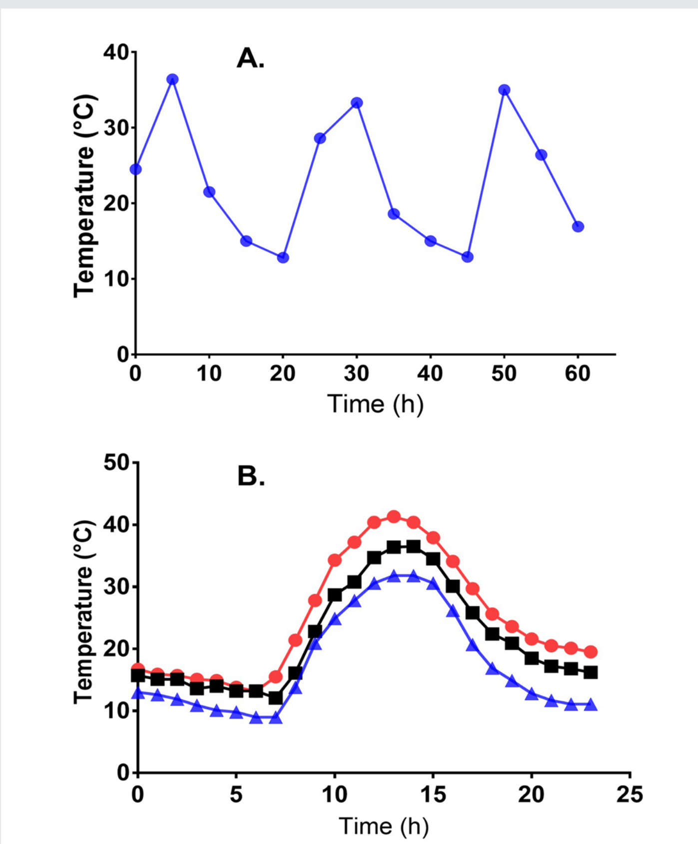

Figure 4. Effect of temperature on pollination. A. Three consecutive day recording and its respective pollination hour. B. Three consecutive months (February, blue triangles; March, black rectangles; April, pale-red circles) recording and its respective pollination hour.

Although in this study, AP had only a single activation temperature (25°C), the AP increased the total clusters per plant 1.2-fold higher compared to the MP (130 vs 108) ($p<0.05$) (Figure 5A). The total number of tomato fruits per plant was also higher for AP in 1.35-fold times than the AP (963 vs 714) ($p<0.05$) compared with MP (Figure 5B). The AP pollinated 90% of the flowers within the first 150 days vs the 75% for the MP (Figure 5C). Hence, extrapolating these results we can assume an approximated total tomato yield of 64000 tomatoes per gutter, i.e., approximately 256000 tomatoes in the whole greenhouse using the AP vs approximated 190000 for MP. Even though in the Pearson correlation, we found a moderate relationship between the days passed and the pollination method, we did not find a significant difference among models (NS) (Figure 5C). The R2 indicates that the adjusted model explains 53% and 61% of the variability in pollinated flowers either for AP or MP, respectively. The correlation coefficient of 0.73 (AP) and 0.78 (MP) indicates a moderately strong relationship among variables.

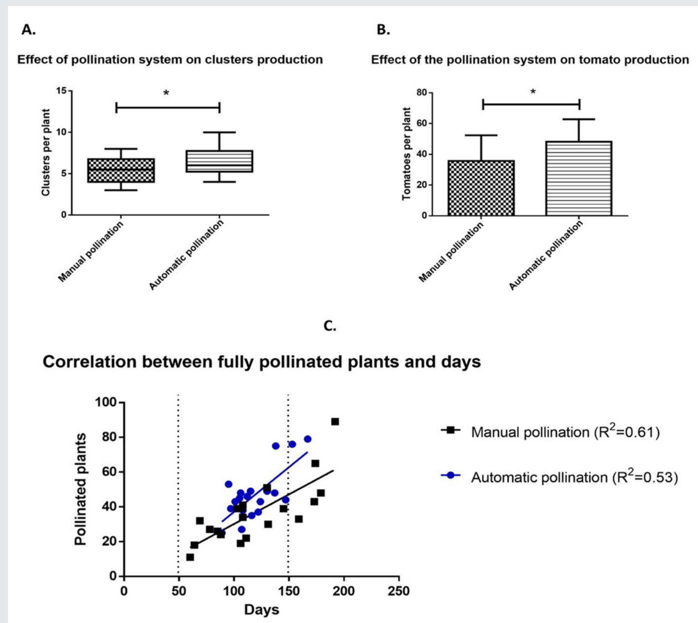

*Figure 5. Manual pollination vs automatic pollination. A. Cluster production per plant (n=20). B. Tomato production per plant (n=20). C. Pearson's correlation between pollinated-plants and days. * p<0.05.*

DISCUSSION

Pollination is the sexual reproduction in plants, this happens through pollen transfer from the anther to a stigma. In this sense, pollination is carried out to produce seeds and, in some cases, fruits. Hence, pollination is an important input during production of marketable goods of many crops, in some crops such as tomato, supplementary pollination is needed; however, under greenhouse conditions this practice is expensive, laborious and unhealthy in some cases. For that reason, is necessary to develop robots to help human labor in agricultural practices, in this scenario, Arduino is emerging as an excellent strategy to construct Hi-Tech and Low cost robots [12].

The tomato flower has mechanisms, which have allowed to achieve up to 98% of self-pollination; however, is not sufficient for fruit production of high quality. It is well known that the size of the fruit depends directly on the quantity of pollen grains that are deposited on the stigma, thus the smaller quantity of pollen the smaller fruits are produced, with deformed seeds. The release of good pollen volumes from the antheric pores requires external agents, mechanical or biological mechanisms, which by vibration can release the pollen and at the time, can modify the physiological conditions of the flower. Conversely, Godfray [13], has estimated that is necessary to grow up the handy man working in agricultural due to 9 billion people has to be feed in 2049.

Garcia [12], showed that the available robots to work on field until now are strongly limited. The next generation of robots must be redesigned, extended and optimized. Also he underlined the necessities of greenhouse mechanization. In this study we tested an automatic tomato plant pollinator and was compared with manual pollination. In order to evaluate whether AP could be more effective than MP where our results the feasibility to use an automatic pollinator and to get more production yield.

On the other hand, Yuan [14], evaluated an autonomous pollinator which is capable to pollinate one cluster in 15 seconds, that is to say, an average time of 150 seconds per plant. In this study, we are capable to pollinate the complete greenhouse in that time.

Another study was carried out using either insect or an automatic bee coated with ionic liquid gels [15], currently, is the most technological approach in the area of automatic pollination; however, a specialized handy man is needed either to program the robot or synthetize the molecules, which represents an extra expense during the crop harvesting.

Nowadays in many countries the labor available in agriculture is declining, greenhouses are not the exception automation and robotic are emerging as production keepers to get the costs down. Just a couple of robot could be called an optimized robot [16], [17]. The AP robot is in the development of conceptual prototype. It is known that is quite complicated to reach the commercialization, just a few robots could be considered as feasible to reach it [17], [18] due to their low operating speed, low success rates and high costs, which gives an extra point to this robot, because the cost of investment (USD $150) is really affordable, the success rate is quite high because it pollinated more flowers than manual pollination (Figure 5) and the operation speed is not a limiting factor, even though it only vibrated once or twice a day is enough to pollinate the most of the flowers.

It is known that tomato is a warm season plant, where temperature plays a very important role in the plant development. It was observed that at temperatures below 10 °C, bloom is negatively affected, while temperatures higher than 35 °C accompanied by low relative humidity performs certain negative effects on the plant such as flower abortion, pollen viability and clusters reduction [19]. In this study, we established 25 °C as an optimal temperature for tomato pollination, to our knowledge we are the first group to propose this temperature as optimal one under greenhouse, since there is no a consensus on what the pollination temperature for tomato under greenhouse conditions could be. However, tomato under field conditions, is well known that success rate of effective pollination is influenced by temperature and humidity. Undoubtedly, 22 to 28°C temperature and 70% to 85% humidity are optimum for good seed set [10].

It is well known that temperature plays a fundamental role during plant development not only necessary for development but also for pollination. Solga [19], corroborated that temperature has a significant effect on flower pollination, is believed to be an outcome of pollen within the anthers. In addition, tomato is a C3 photosynthetic plant, which requires optimum pollination temperatures ranged from 18 to 27°C [20].

CONCLUSIONS

Our robot is still in the proof of concept. It is necessary to improve it; however, the robot could work up to 5000 h, without the necessity of any calibration before or during the season. The results showed that 25 °C is an excellent temperature for supplementary pollination. Furthermore, during the first 150 days the pollination with the robot was higher than the traditional pollination (90 vs 75% for AP and PM). More tomatoes and clusters per plant were developed using the AP with a total of 963 (48.2 ± 14.6) tomatoes versus 714 (35.7 ± 16.7) ($p < 0.05$) and 130 (6.5 ± 1.6) vs. 108 (5.4 ± 1.5) ($p < 0.05$) clusters per plant. The 6 month production costs was 5.4 times cheaper than the PM. The robot could detect temperature and humidity during all the study. Therefore, the operational conditions were established, the robot was able to perform its activation automatically according to the set point parameters. It is mandatory a better instrumentation with more robust sensors to control several processes during the performing of the AP in order to get the final stages (Technological product).

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