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Bibliographic review

The reproduction of potato (*Solanum tuberosum* L.) tubers from their sexual seed

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ABSTRACT

Potato (*Solanum tuberosum* L.) is one of the most important food crops worldwide, due to its high nutritional values, its great demand among the population and its high production in a short time. For its propagation, propagules or tubers are used, which in Cuba are imported and they are very expensive; therefore, the objective of this review was to update the art state of potato tuber propagation from its sexual seed at international and national level. The review of the international bibliography showed that the research carried out has been aimed at obtaining new varieties, within the specialty of genetics and, in Cuba, the works carried out three decades ago were not concluded, so that an alternative technology has not yet been achieved for farmers to have access to the use of this technique. There is also no information available to show what remains to be done to achieve this goal. The results of the review allowed visualizing the benefits and limitations of this productive modality, for its possible economic, ecological and social benefits, if its implementation were achieved in Cuba, something that is not investigated at present.

Key words: food sovereignty, sustainability, technology, propagation, tubers, resilience

INTRODUCTION

Potato is today one of the most important crops in the world food diet, ranking fourth after rice (*Oryza sativa* L.), wheat (*Triticum* spp.) and maize (*Zea mays* L.) [(1)]. It has an annual production of 321.9 million tons on 18.6 million hectares, for an average yield of 17.3 t ha^{-1}. China is the world's leading potato producer with 73.7 million tons, followed by the Russian Federation with 36.4 t ha^{-1}, India with 25.0 t ha^{-1} and Ukraine with 19.3 t ha^{-1} [(2)].

According to the Ministry of Agriculture and Irrigation in Latin America, Peru remains the main potato producer in the region with an annual production of 5.3 million tons registered in 2019, whose volume serves to mitigate the food needs of that country, which has a population of 32 million consumers. This production volume of the Andean tuber, confirms Peru with the 14th place, among potato producers worldwide, only surpassed in descending order by Canada, Turkey, Iran, France, Belarus, Netherlands, Germany, Ukraine, United States, Poland, India, Russia and China, which occupies the first place [(3)].

In Cuba, potato ranks first in production, among root and tuber crops, and an average of 7 515 ha are planted annually, with an average yield of 22.02 t ha^{-1} and an annual production of 165 508.6 t [(4)].

All the potato produced worldwide is made through the use of tubers as planting material, from which Cuba is not exempt, with the disadvantage that such planting material is imported, mainly from Europe, together with a technological package for its production at too high a cost. This reality and considering the need to reduce imports to a minimum [(5)], it is necessary to find other more sustainable and resilient alternatives, which accompany the established technologies and, at the same time, contribute to increase its cultivation surface, with productive profitability towards a greater approach to Food Sovereignty [(6)].

The reproduction of potato seed, through sexual seed, is an ancestral technique, derived from the first settlers of South America, the center of origin of this solanaceae [(7)].

However, the growing food demands on a global scale have caused the abandonment of traditional techniques, replaced by those that generate greater productivity over time, due to the growth of large cities, which demand large volumes of food in a short time and the demands of quality and uniformity imposed by the dynamics of international trade.

Potato, in particular, is a food consumed by more than one billion consumers worldwide, according to estimates, which has generalized propagation by propagules, which seems to be the most productive method in less time [(2)].

Cuba, which has scarce financial resources, imports at a high cost, all the propagules for the annual plantations, without the existence of a reproductive alternative to avoid imports or to contribute to supply the national demand. The reproduction of tubers through botanical seeds is an option that could be more sustainable and resilient for Cuba, to increase the production of this demanded food. For these reasons, the objective of this review was to achieve an update on the state of the art of potato tuber reproduction, from its sexual seed at international and national scale; this will allow visualizing its benefits and limitations and the possible economic, ecological and social benefits with its implementation in Cuba.

Importance of potato reproduction through botanical seed

The literature reviewed indicates the existence of other planting alternatives through tubers, such as the use of buds that sprout from the tuber after its dormancy period, which allows a considerable increase in the number of plants per tuber. The production of seedlings through tissue culture, a novel method of

agricultural biotechnology, and the production of tubers from botanical seed, which is included in the literature as an option whose main use has been in works for the propagation of varieties of genetic interest. The analysis of this review focuses on this last option [8].

Potato can be reproduced through its sexual seed, also known as botanical or true seed and by its acronym in English as TPS (True Potato Seeds) [5,6]. To achieve this, seeds are extracted from the berries and they are then used as reproduction material, an innovative technological option of low cost, since tubers obtained are free of many viruses and diseases and, even when there is no economic study of its costs, it is considered that this technique is relatively cheap, it does not require large refrigerated capacities for its conservation and the material resulting from its obtaining process is much easier to transport [9].

Sexual seed potato is currently used by farmers in at least a dozen countries, including China, India, Nepal, Bangladesh, Vietnam, Peru, Nicaragua, and Venezuela. Estimates of areas cultivated with sexual seed potato and planting materials derived from it are difficult to acquire because estimates depend on the extent to which subsequent generations of sexual seed potato materials can be traced and included in the estimates [10].

But the greatest importance of potato production from botanical seed is that it could be used by producers in situ and dispense with imported seed, which, moreover, it is very expensive. Although the commercialization of the product obtained may not be very attractive for marketing, due to its diversity of colors and shapes, it is still an important alternative for feeding families and neighbors in rural communities, not to mention its importance for animal feed [11].

Retrospective analysis of potato breeding technology from sexual seed on an international scale

The literature reviewed makes reference to the fact that the potato was domesticated by the ancestors of Andean farmers and it was cultivated at least 7000 years ago. According to the distribution of the first known cultivated potatoes and the most related wild species, it seems likely that the cultivation of this tuber began in the Lake Titicaca region, between 3,500 and 4,500 meters above sea level. It is also in this region where there is the greatest variation in its cultivated forms and corresponding wild species [2].

With the passage of time, Andean man obtained hundreds of varieties, extending potato cultivation throughout almost the entire Andean region, occupying the high regions of Colombia, Ecuador, Peru, Bolivia and Chile. This period coincided with the arrival of the Spaniards in South America, who introduced it in Europe at the end of the 16th century, and it was subsequently dispersed throughout the world, due to commercial exchange [12].

Historically, it has been widely discussed about the species that gave rise to the potato cultivated between 6000 and 100,000 years ago, in the Andes of southern Peru.

Taking into account morphological and phytogeographical features, it is believed that *S. stenotomum* originated from the wild species *Solanum bukasovii*, *S. canasense* and *S. multissectum*, belonging to the *S. brevicaule* complex, which is considered the first domesticated potato. This, in turn, would have given rise to *S. andigena*, through repeated processes of sexual polyploidization in different cultivation areas, with the consequent interspecific and intervarietal hybridization, which allowed expanding the diversity and genetic adaptability of the Andean potato. Evidence from Andean folkloric history shows that highland farmers used sexual seed to periodically clean their planting materials and increase production [13].

Potato reproduction through sexual seed in modern times

The first research on sexual seed potato of the modern era was carried out in the People's Republic of China, in 1959, and already in the beginning of 1960, started to produce on a large scale with this type of seed; therefore, this country is considered a pioneer in these studies [14,15].

In Latin America, it was the International Potato Center (CIP, according its acronyms in Spanish) that in 1977 initiated a study on genetic improvement and agronomic experiments that became known as the technology for the reproduction of SSP. The first presentations on the subject were published in 1983-1984 in the Proceedings of Potato Research for the Year 2000 [16] and at the 28th Planning Conference on Innovative Methods in CIP for Potato Propagation [17].

An intense program of agronomic research was carried out by CIP's Department of Physiology at its headquarters and experimental stations located in Peru during the 1980's. From the agronomic point of view, the starting point was the experience developed by growing SSP seedlings produced from crosses. But in particular, reports of the innovative technology of extensive use of sexual seed potato (SSP) reported in China increased the enthusiasm in CIP circles. Thus, by 1984, more than 34 countries were experimenting with SSP and the results were used by farmers in five countries in the region [18].

There is also evidence of occasional use of botanical seed in Peru and Bolivia, such references to the use of this technique were described by the descendants of the Incas in the vicinity of Cuzco [19].

In 1989, Burton in his book "The Potato" in its (third edition), had integrated a chapter on propagation by botanical seed and since then, the technology has been experimented, integrated and adapted to a wide range of countries. In the 1990s, CIP reduced its research related to SSP, until it was phased out in the first decade of the 21st century, the 2000s. By this time, sufficient knowledge was available to formulate protocols for dormancy breaking and seed quality testing [10].

The positive experiences of experimentation with SSP in Central Asia have made it clear that this technology maintains the attraction of new countries and seed producing companies, which is reflected in the requests for courses on the subject, especially among researchers from Latin American countries.

However, not all options for improving the technology are fully explored. The technology can be further improved, especially through research related to genetics and seed quality [12].

Sexual reproduction of potato in Cuba. Its importance

The oldest reference found on the sexual reproduction of potato in Cuba goes back to the results of the crossings carried out in the decade of the 80's of the XX century, with the purpose of selecting clonal varieties. The literature mentions that through the botanical seed, most of the viruses are not transmitted through it [10], except: the virus from the available material.

In the 90's of the 20th century, a research project was initiated on this subject called potato production from sexual seed. The experiments were conducted at the National Institute of Agricultural Sciences and at the Liliana Dimitrova experimental station and the extension of results, in Isle of Youth special municipality. Aspects such as the selection of hybrid progenesis, fertilization and seed management were evaluated. Some of these results were reflected in the Guide for the production of potato seed tubers from sexual seed [12]. At the end of the project, these studies were not continued. At present, there is a genetic improvement project and technology for obtaining botanical seed, which is being developed at INCA.

However, there are still no conclusive results, reasons that advise to continue deepening in the subject, until achieving a technology on agroecological bases that makes possible its use in the productive practice, which would contribute to the Food Security of the country in times of scarce financial resources and would respond to the call of Cuban Science to work for the reduction of imports.

In Cuba, the production of tubers to be used as "seed" represents between 40-70 % of the cost of production. The high populations of aphids and other insects, in addition to the presence of diseases throughout the year, make it difficult to develop a national seed potato program, so it is imported every year with its technological package [20].

On the other hand, if it were possible to produce potato from botanical seed, abundant enough to supply needs of the communities, through the participation of local farmers, the importation of tubers as "seed" would gradually decrease, making the potato production process more sustainable and robust, in favor of the country's food sovereignty, even though the purpose of implementing an additional program is not intended to replace the established one.

Advantages and limitations of potato propagation by botanical seed

Main advantages of potato propagation through botanical seed

When tuber production comes from botanical seed, genetic variability is rescued; plants obtained from botanical seed have tap roots, which can favor better anchorage and absorption of water and nutrients.

Production is obtained with high levels of health, potatoes free of nematodes, insects, bacteria, fungi and most viruses. In addition, tubers from botanical seed can be produced in national multiplication programs as basic seed, or also by individual or cooperative farmers, since it is easy to distribute botanical seed to any potato-growing area, so that first-generation tubers can be produced as seed in the proximity of areas where potatoes are produced for consumption and avoid the transportation of tubers-"seed" from long distances [21].

Another important benefit of the use of SSP is its technological flexibility, since seeds can be sown directly in the field, transplanted and produced in seedbeds. The harvested tubers can be sent to market or used as breeding material [10].

Aspects that have to do with economic profitability and Food Sovereignty

To plant one hectare of potato, farmers require 2 to 5 tons of tubers, which, if not used as planting material, would be used for consumption; however, through botanical seed, 50 to 150 grams of sexual seeds are enough to plant the same area. The cost of the SSP to install one hectare, constitutes 2.4 % ($USD 30.00) of the cost of the volume, equivalent to that of the tubers, to plant the same surface ($USD 1,250.00) and eliminates, at the same time, the high costs of transport of these last ones, from their place of production [9].

Sexual seed also provides the farmer with greater independence in deciding the convenience and opportunity for planting, since its storage is not conditioned by the bud break [2].

The main advantage of the use of sexual seed is the possible incorporation into potato production of a high potential of farmers who would not depend on imports that are currently made for domestic production [10].

Main disadvantages of potato propagation through botanical seed

SSP also has some disadvantages, among which the most significant are the following: it requires more work and demands a change of habits; it requires varieties that flower adequately; it produces less uniformity in the size of the tubers and there is no certified seed available to guarantee quality; it has a longer cycle that is more vulnerable to biotic and abiotic factors [22,23].

However, most of the limitations could be overcome through research that could be carried out prospectively, depending on the improvement of the technology. Besides keeping in mind the changes that are being generated in the climatic conditions for the spatial and temporal establishment of sowings in a convenient and opportune way.

Technological aspects that are decisive for the SSP

The most relevant technological aspects are shown in Figure 1.

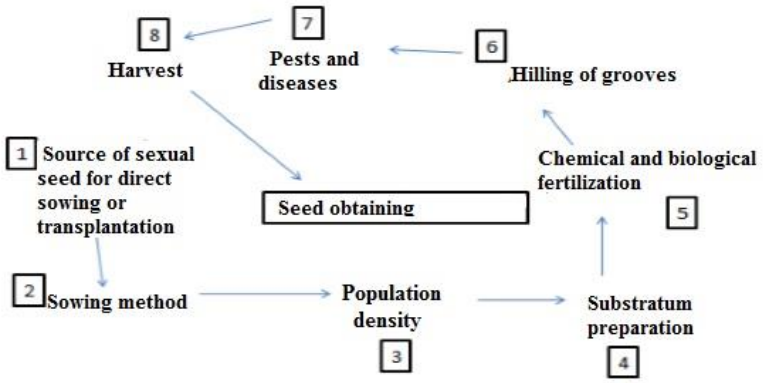

Figure 1. Outline of the main technological aspects of the SSP

Seed potato sexual seed sources

The source of sexual seed potato production lies in the ability of a given variety to flower, be fertilized naturally or artificially and form berries that contain the seeds, which after maturity will be extracted for use in planting.

Open-pollinated seed can be produced at low cost and good tuber yields have been achieved with it. It is important that berries are collected from the best local varieties. After extracting the seeds from the berries, small, dark-colored seeds should be removed, because they have poor germination and growth [(10)].

In Cuba, researchers have learned to use the best combinations of parents to produce hybrid sexual seed; for example, TS-6 x TPS-67 and Serrana x TPS-113 [(24)].

Phytotechnical activities

Seeding method

SSP can be used for the production of propagules for new planting or for feeding, which is achieved in three different ways: direct sowing to field, planting in beds at high densities to produce mini-tubers and seedbed in beds for transplanting seedlings to field [(25)].

The production of the first generation of seedling tubers is determined by the climatic conditions of the locality and the local agricultural systems that impose the characteristics of production in terms of yield and tuber size [(12)].

Sexual seed can be used for two different purposes: where potatoes can be produced directly in the field, from seed and in order to produce tubers to be used later as "seed" in a second harvest or even in repeated generations [10,25].

There are different sowing methods for tuber production: direct sowing in beds and transplanting of seedlings to beds [26].

Direct sowing in beds consists of sowing three or four seeds per nest at a distance of 10 x 10 cm; after emergence, the plants are thinned until 100/m^2 are left.

Transplanting of seedlings to beds consists of the following: the plants are grown in trays and transplanted to the beds 35 days after sowing, at a distance of 10 x 10 cm (this method requires more labor and delays the vegetative cycle of the plants by 20 days, due to the stress of transplanting).

When the two sowing methods were tested: direct sowing and transplanting [27], it was observed that the plants transplanted at 35 days suffered a delay of 10 days, compared to those of direct sowing and that more than 90 % of the tubers of direct sowing were formed between 45 and 55 days after sowing, while those of the transplanted plants were formed between 35 and 63 days later.

The total number of tubers at final harvest was similar in the two sowing methods, with a total duration of 110 days for direct sown plants and 125 days for transplanted plants.

The most commonly used technology is the production of tubers in beds.

When SSP is used in beds, there are fewer requirements for good germination and seedling growth. In addition, tuber seedling production does not require high transplanting inputs, plants do not suffer stress, and management is better controlled in small protected areas than in the field [23,28].

Density of population in beds for tubercle production

A high plant population has a positive effect on the number of usable tubers produced per unit area. Studies of stocking density in CIP show that the optimum plant population, after thinning, should be at least 100 plants/m^2; to obtain this stocking density, botanical seed can be sown 10 cm apart between rows and two to three centimeters between seeds. Then the plants are thinned in each row, leaving more or less 10 cm between plants; thus a final distance of 10 x 10 cm between plants is obtained [21].

Sowing is done in points (nests) and the distance between each point should be 10 cm, obtaining 100 sowing points/m^2 -bed; in each point two or three seeds are deposited at a depth of 0.5 cm and then lightly covered with soil or substrate. After thinning and replanting in the points without plants, one plant should remain as a planting point. This density makes it possible to produce vigorous seedlings, increases air circulation and reduces the occurrence of fungal diseases, such as seedling drop and others that attack the foliage [10].

In experiments previously carried out by the author, testing two population densities of 50 and 100 plants/m^2, the highest number of total tubers was obtained with 100 plants/m^2 of different calibers in great number, except calibers greater than 40 g, in which the number of tubers was equal to the number of plants [27].

Substratum preparation

Potato seedlings need a substrate containing a high percentage of organic matter and a very limited amount of clay. Too much clay hardens the substrate. A suitable substrate, measured in volumes, can be: four parts sand + four parts organic matter (compost or moss) and 0 to two parts loam or organic soil [21].

With the combined use of substrate in a 4:1 ratio of soil + cow manure, the use of biofertilizers in the co-inoculation of plants and a nitrogen pulse of 60 kg ha^{-1}, better results were obtained than when chemical fertilizers were used [29].

Some authors carried out studies where they tested three substrates: soil+cattle (2:1), soil+cattle manure (2:1) and soil+chemical fertilization, using two sowing methods (direct and by transplanting), obtaining satisfactory results with the substrate soil+cattle manure (2:1), both for the number of tubers per m^2, as well as for the fresh mass per m^2 [30].

When using different proportions of Ferrallitic Red soil compacted with cattle manure (2:1, 3:1 and 4:1), the best results were obtained with the 4:1 proportion, equivalent to 11.6 kg of manure/m^2 (86 t ha^{-1}) wet basis with 25% humidity [31].

Chemical and biological fertilization

Two weeks after germination (approximately 24 days after sowing), the first foliar fertilization is carried out, applying 10 liters of solution per 5 m^2 of beds, with a proportion of 1 gram of urea per liter of water. The second foliar fertilization is carried out six days after the first one, with a proportion of 2 grams of urea per liter of water [12].

The first fractional fertilization should be carried out 15 days after sowing, applying 275 g of urea or 390 g of ammonium nitrate; the second at 22 days after sowing, applying 623 g of urea or 917 g of ammonium nitrate and the third at 22 days after sowing, applying 623 g of urea or 917 g of ammonium nitrate and 780 g of potassium sulfate [25].

With the inoculation of potato sexual seeds with biofertilizers, such as *Pseudomonas fluorescens*, *Pseudomona scepacia*, *Azospirillum brasilense* Sp-7 and the co-inoculation *Azospirillum brasilense* Sp-7+Mycorrhiza *Glomus fasciculatum*, sown in beds with soil+cow manure substrate at a ratio of 4: 1 and an application of 60 kg N ha^{-1}, it is possible to obtain higher yields in seed tubers per hectare than with

traditional methods, with the consequent saving of chemical fertilizers and preserving the ecological balance of the ecosystem [29].

Hilling in flowerbeds

The maximum production of tubers per plant depends on a good application of soil around the plant to support it. If the earthing up is deficient, the stolons, when exposed to the air, do not become tubers but branches. Two hilling operations are carried out, the first immediately after thinning and the second 15 days later [24,25].

After the second hilling, the stems should be covered 4-6 cm above the initial level of the bed, the final conformation of the small furrows should be rounded in each row of plants and thus ensure that the roots and stolons do not come to the surface [12].

Hilling tends to increase the number of tubers per plant; it can also provide better protection against pests. Hilling can be affected by adding a layer of soil 4 to 6 cm high to the seedlings, dividing this amount into two hilling operations. The ridging should be completed before the plants touch each other [10,25].

Pests and diseases. Its management

Plant pathogens, such as nematodes, fungi, bacteria, mycoplasmas, viruses and viroids, can be transmitted from diseased plants to seed tubers. However, when propagation is by sexual seed potato these common potato diseases are not transmitted from diseased plants to sexual seed; therefore, they do not carry many of them. Only very few virus diseases and one viroid, so seed tubers from sexual seed potatoes have excellent phytosanitary quality, so they will not transmit many diseases to the next generation either. Well-documented reports of disease transmission by sexual seed potato are: potato T virus, tuber blight viroid, tobacco mottle virus, and Andean potato latent virus [32].

Harvest

Normally between 90-120 days after sowing, depending on the progeny used, plants will be ready to be harvested, which is recognized by a general yellowing. The foliage is then cut at ground level for harvesting 10-15 days later. Tubers that are exposed to the sun after defoliation should be covered with soil to prevent rotting. Light irrigations are applied during this stage to maintain soil moisture and fluffiness [10].

Seed preservation

Seed tubers from SSP should be stored under the same requirements of the Ramal Standard for potato crops, with the difference that sizes smaller than 30 mm should be stored in boxes of no more than 25 kg [12].

CONCLUSIONS

The SSP technology for potato production is a viable, pertinent and appropriate alternative that is adapted to the conditions of Cuban farmers for its possible implementation, which will undoubtedly contribute to local food security without the use of external resources and imported inputs.

RECOMMENDATIONS

4. That a program aimed at the production of sexual seed potatoes be initiated to put this alternative into production practice, with a view to increasing the availability of potato reproductive material for consumption and strengthening the availability of propagules for potato reproduction.
5. To develop, simultaneously, an investigation that defines the economic viability of the new proposal, assuming as a reference the expenses incurred for its acquisition, through its importation.
6. That research be initiated to solve problems related to genetic improvement and improvement of the phytotechnical management of potato cultivation during the process of tuber reproduction on agro-ecological bases.

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