Communication

Challenges in the Production of High-Quality Seed Potatoes (*Solanum tuberosum* L.) in the Tropics and Subtropics

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Abstract: The potato has been a widely used vegetable crop in temperate countries for a long time. Its consumption and the area of its cultivation has increased significantly over the past decades in the tropics and subtropics as well. The main problems of potato producers in the tropics and subtropics are the unsatisfactory quality of seed potatoes, mainly derived from the informal seed supply system, and the insufficient availability and high cost of certified seed potatoes. The hope for improving this situation can be the application of soil-less technologies for minituber production under controlled conditions. This publication focuses on important advantages of the aeroponic system in the production of pre-basic seed potatoes in the tropics and subtropics. It also highlights some deficiencies that can be overcome with the involvement of several actors in the potato industry, including local universities and the private sector. It emphasizes that innovative aeroponic installations are an opportunity to increase the production of high-quality seed potatoes in the countries of the tropics and subtropics, which, in many cases, will result in less dependence on expensive imported seed potatoes, often from a different climate zone. The introduction of aeroponic installations conserves the shrinking natural soil and water resources and contributes to their protection.

Keywords: aeroponics; high-quality seed potatoes; potato yield; pre-basic seed potatoes

1. Introduction

The potato (*Solanum tuberosum* L.) is grown on all continents inhabited by humans except Antarctica. Climatic conditions, including the temperature during the whole growing season, are fundamentally important for the proper development of plants. Studies by Ingram and McCloud [1] have shown that 22 to 24 °C is the optimal temperature for potential root and canopy growth of potatoes and 14 to 16 °C is the optimal temperature for potential tuber growth. That is why modern potato cultivation works best in temperate climate conditions.

The potato has a poor tolerance to high temperatures during the tuberization period, which is particularly unfavorable from an economic point of view. Hope for growing potatoes at higher temperatures was brought by the latest laboratory tests by Lehretz et al. [2] which revealed a mechanism that inhibits tuberization at high temperatures.

In the temperate climate zone (Europe, North America, northern China), the potato is a lowland crop and its production falls in the summer period [3]. In the 19th century, the potato was one of the most popular crops in Europe. Nowadays, its production has declined, but the potato remains a prominent crop, occupying the third place in terms of total production quantity on this continent [4]. The growing popularity of processed potatoes seems to testify to the changing preferences of consumers. In the temperate climate zone, the potato is also widely used as a raw material in the spirit and starch

industry and as animal feed. However, during the 20th century, the use of potato tubers in animal nutrition decreased significantly and led to a substantial drop-off in their production in many countries. Based on FAOSTAT data [4], over the past 50 years, potato production in Poland, Ireland, Germany and Italy has decreased by 81.0%, 76.4%, 66.9% and 66.4% respectively (Table 1).

The situation is different in countries of the tropics and subtropics, including areas with high population density. According to Hijmans [3], in areas such as the Nile Valley or the Ganges Plain, a large increase in the use of potatoes for direct consumption and thus, in their production, has been noticeable in recent years (Table 1). The potato appears more and more often as an integral part of multiple cropping systems characteristic of the tropics and subtropics because it has an extremely high production potential, is a valuable source of energy and protein and its cultivation is profitable and provides employment [5]. In tropical countries such as Bolivia, Columbia, Peru, Ethiopia, Kenya and Uganda, potatoes can be grown all year round. Their cultivation is concentrated in the cool highlands, even at an altitude of up to 4000 m a.s.l. [3,6–8]. On the other hand, in countries of the subtropical zone, such as Egypt, Bangladesh, India and southern China, potato cultivation takes place in the cool season (winter, autumn or spring) and is limited to lowlands and mid-elevations [3].

Currently, most potatoes are produced in Asia and Europe, yielding respectively 50.4% and 31.4% of the world production. Over the past 50 years, the share of individual continents in global potato production has increased, with the exception of Europe (Table 2).

As far as the percentage share of the global potato growing area is concerned, the importance of the European continent has decreased in favor of areas of cultivation in Asia and Africa (Tables 1 and 2). For example, while over the past 50 years, the area of potato cultivation in Poland decreased by 88.0% in Egypt, Bangladesh, Kenya and India, the area of its cultivation increased by 838.9%, 609.8%, 599.4% and 360.4%, respectively, over the same period of time. Tables 1 and 2 also show that the observed increase in potato production in Asia and on the African continent goes hand in hand with the expansion of the potato growing area. As noted by Tessema and Dagne [9], many farmers are trying to meet the growing demand for potatoes by expanding their area of production rather than overcoming factors that limit productivity.

The average world potato yield in 2017 was 20.11 t/ha [4]. Over the past 50 years, a noticeable increase in yield relative to the world average has occurred on all continents and in many countries (Tables 1 and 2).

Potato yield depends not only on the already mentioned climatic conditions during the growing season. The health conditions of the plant itself are also very important. That being said, it should be emphasized that the quality of seed potatoes is the most important yield-determining factor that a farmer can influence. It is also the most important crop reduction factor in many potato-growing countries [5,10].

Table 1. Production (in tonnes), area harvested (in ha) and potato yield (in hg/ha) in selected temperate countries and some countries of the tropics and subtropics, as well as changes in production, area harvested and potato yield over 50 years (1967–2017) *.

Countries	Production			Area Harvested			Yield		
	1967 (Tonnes)	2017 (Tonnes)	Changes over 50 Years (%)	1967 (ha)	2017 (ha)	Changes over 50 Years (%)	1967 (hg/ha)	2017 (hg/ha)	Changes over 50 Years (%)
Temperate zone									
France	10,406,250	7,342,203	−29.4	515,415	173,486	−66.3	201,900	423,216	109.6
Germany	35,358,912	11,720,000	−66.9	1,393,136	250,500	−82.0	253,808	467,864	84.3
Ireland	1,747,700	412,400	−76.4	64,600	9200	−85.8	270,542	448,261	65.7
Italy	4,009,600	1,346,936	−66.4	339,090	48,571	−85.7	118,246	277,313	134.5
Netherlands	4,840,196	7,391,881	52.7	138,178	160,791	16.4	350,287	459,720	31.2
Poland	48,213,696	9,171,733	−81.0	2,741,200	329,323	−88.0	175,885	278,503	58.3
USA	13,872,474	20,017,350	44.3	591,043	415,010	−29.8	234,712	482,334	105.5
Tropics and subtropics									
Bangladesh	600,500	10,215,957	1601.2	70,400	499,725	609.8	85,298	204,432	139.6
Brazil	1,466,521	3,656,846	149.3	217,423	118,030	−45.7	67,450	309,823	359.3
China	17,923,043	99,205,580	453.5	2,001,847	5,767,481	188.1	89,533	172,009	92.1
Egypt	278,480	4,325,478	1453.2	17,461	163,939	838.9	159,487	263,848	65.4
India	3,521,500	48,605,000	1280.2	473,300	2,179,000	360.4	74,403	223,061	199.8
Indonesia	85,000	1,164,743	1270.3	18,000	75,611	320.1	47,222	154,044	226.2
Kenya	195,000	1,519,870	679.4	27,500	192,341	599.4	70,909	79,020	11.4
Peru	1,711,741	4,776,294	179.0	271,895	310,400	14.2	62,956	153,875	144.4
Uganda	130,000	165,000	26.9	15,000	39,300	162.0	86,667	41,985	−51.6
World	296,220,305	388,190,674	31.0	21,400,798	19,302,642	−9.8	138,416	201,108	45.3

* calculated after FAOSTAT.

Table 2. Production (in tonnes), area harvested (in ha) and potato yield (in hg/ha) on continents and their percentage share in relation to the world average in 1967 and 2017 *.

Continents	Production				Area Harvested				Yield			
	1967		2017		1967		2017		1967		2017	
	Tonnes	in Relation to the World Average (%)	Tonnes	in Relation to the World Average (%)	ha	in Relation to the World Average (%)	ha	in Relation to the World Average (%)	hg/ha	in Relation to the World Average (%)	hg/ha	in Relation to the World Average (%)
Africa	2,379,578	0.8	25,011,823	6.4	287,765	1.3	1,892,633	9.8	82,692	59.7	132,154	65.7
Americas	24,258,477	8.2	44,173,458	11.4	1,777,514	8.3	1,797,479	9.3	136,474	98.6	245,752	122.2
Asia	30,143,122	10.2	195,668,682	50.4	3,159,826	14.8	10,209,139	52.9	95,395	68.9	191,660	95.3
Europe	238,561,585	80.5	121,761,565	31.4	16,127,192	75.4	5,365,045	27.8	147,925	106.9	226,953	112.8
Oceania	877,543	0.3	1,575,147	0.4	48,501	0.2	38,345	0.2	180,933	130.7	410,780	204.3
World	296,220,305	100.0	388,190,674	100.0	21,400,798	100.0	19,302,642	100.0	138,416	100.0	201,108	100.0

* calculated after FAOSTAT.

2. Some Aspects of Seed Potatoes Production in the Tropics and Subtropics

Potato tubers are a special seed material because they can carry many disease-causing organisms. Some soil-borne pathogens such as bacteria, fungi and nematodes accumulate in the soil and attack the underground parts of the plant during the growing season. Other air-borne organisms, such as *Phytophthora infestans* (Mont.) de Bary, first infect the leaves and then accumulate in the tubers. Tubers can also be a source of vector-borne pathogens, such as viruses, often transmitted by aphids.

Seed-borne diseases with negative economic effects in the tropics and subtropics that affect the potato are primarily bacterial wilt caused by *Ralstonia solanacearum* (Smith 1896) and virus diseases caused by PVY, PVX, PLRV and PVA [11].

The health status of tubers in the tropics and subtropics leaves much to be desired. Data collected by Gildemacher et al. (2019) show that only 3% of seed potatoes sold on the markets in Kenya were virus-free and the endemic bacteria *R. solanacearum* was found on 74% of farms [11].

Tubers attacked by pathogens undergo gradual degeneration. The degeneration of tubers negatively affects their quality and leads to a yield reduction in subsequent cycles of vegetative reproduction [12].

Incoming research results confirm that the poor quality of seed potatoes is one of the main factors limiting yield in many regions, such as sub-Saharan Africa. This was confirmed by potato growers in Kenya, Uganda and Ethiopia [11]. Experts have proven that the probability of potato growers identifying seed potatoes of poor quality as important or very important problems was 95%. Potato farmers in sub-Saharan Africa are able to increase potato production by 140% as long as they have access to high-quality seed tubers and improved production technologies [13].

The accumulation of pathogens in the soil and their rapid spread take place in the informal or local supply system for seed potatoes, which is very common in the tropics and subtropics. The informal supply system involves the use of tubers from the production of ware potatoes harvested in the field during the previous season as seed potatoes. It is very popular in Kenya, for instance, where 50% of farmers declare total dependence on farm-saved seed. Many of them also obtain seed potatoes from their neighbors or at local markets [11]. Such seed potatoes are of poor quality, sometimes with an inadequate physiological age, mixed up in varieties, physically damaged, inadequate in size, and often stored in poor conditions [14,15].

Many potato growers never renew seed tubers. This applies to over 50% of growers in countries such as Kenya, Uganda and Ethiopia. Those who renew them, do so after three to eight seasons, on average [11]. The long-term use of tubers from field production as seed potatoes contributes to the accumulation of pathogens in them, leading to their degeneration and a decrease in their quality and yield.

It is worth noting that in temperate climate countries, it is even possible to exchange seed potatoes every season with high-quality seed tubers [10].

Part of the informal seed supply system is the so-called specialized chain, mentioned by Gildemacher et al. [11], in which the production and sale of seed potatoes is a business activity, but this system does not guarantee the implementation of quality control mechanisms and the seed potatoes produced are not certified. Seed growers usually have a reputation of selling quality seed potatoes among nearby farmers, but they do not comply with formal quality control and certification regulations. In addition, the average seed potato multiplication rate by seed growers is usually low, which can be explained, among other factors, by the lack of irrigation facilities. Nowadays, this system does not seem to be very popular. Less than 5% of Kenyan farmers declare their seed potatoes to be supplied by specialized growers.

It should be emphasized that local farmers sometimes receive financial and technical support from NGOs and university breeding centers. Such an alternative seed production system involves cooperation of farmer cooperatives with the public research and extension system. Public research organizations are a source of disease-free seed potatoes and can invest in the development of cost-effective techniques used in modern production of minitubers. This alternative supply system can

work well in countries where there is a lack of high-quality seed potatoes. For example, in Ethiopia, where 98.7% of seed potatoes come from the informal system and the formal system is in its early stage, 1.3% of healthy seed potatoes are supplied by such alternative system [9,11,14,16].

The controlled production of seed potatoes in the formal supply system is different. Seed potatoes are produced by licensed private sector specialists and cooperatives. The application of national legislation and international standards favors the production of high-quality disease-free seed potatoes. These certified seed potatoes provide higher yield in potato production. In addition, the application of fertilizers, irrigation and adequate crop management in commercial production can be more effective when using high-quality seed potatoes. Using high-quality healthy seed potatoes enables farmers to reduce their use of environmentally harmful plant protection products [10,14,17].

The production of certified seed potatoes in the tropics and subtropics faces some challenges. For example, such seed potatoes can be too expensive for end users, there can be a very limited supply, and the conventional process of growing them in the soil is relatively long.

One of the main economic problems in the production of high-quality seed potatoes is their cost to end users. The price of such certified seed potatoes places them out of range for the vast majority of farmers with limited resources. Such seed tubers can account for 30% to 70% of total production expenses [10]. In Kenya, for example, the price of certified seed potatoes accounts for 42% of the total production costs and in India their cost ranges from 40 to 50% of the total production costs [15,18].

In many countries, even those leading in potato production, another problem is the shortage of high-quality seed potatoes. It is also often one of the most significant factors that hinder the development of the potato industry. It is estimated that in China, which produces 25.6% of all potatoes in the world [4], only about 20% of the area dedicated to seed potato production is planted with high-quality certified seed [7]. The quantity and quality of raw materials available do not meet the requirements of the growing potato processing industry in this country.

The production of certified seed potatoes in India covers 55% of the demand [19]. In Bangladesh, which is currently seventh in terms of potato production in the world, certified seed potatoes cover less than 10% of the demand [4,8].

In Indonesia, 7.4% of farmers use certified seed potatoes. Their availability is at the level of 6% in relation to the total demand [20].

In Latin America, except for a few countries such as Brazil, in which 20–30% of seed potatoes are certified [21], the area planted with certified seed is only a small part of the total area dedicated to potato cultivation, which means that the use of certified seed potatoes in relation to all planted seed potatoes ranges from 0.24% to 3.01% [22].

The situation on the African continent is even worse. In Kenya, coverage of domestic demand for certified seed potatoes is only 1% [23].

If one correlates % of certified seed tubers from several countries and final tuber yield, then the positive high correlation coefficient (0.81) indicates the close dependence between these two elements.

The modern global production of seed potatoes is moving towards reducing the number of plantings in the field to a minimum, among others, due to the constant threat of pathogen infection. It is common practice for many seed potato production programs to produce high-quality seed after two or three generations in the open field instead of three to five or even five to seven years using the conventional soil method [10,22,24].

Supplying producers with high-quality seed potatoes is very important. In many countries, small producers compensate for the inability to purchase certified seed potatoes by using tubers from ware potato production for planting while at the same time exposing them to degeneration and low yield. On the other hand, larger farms solve this problem mainly by using certified, imported seed potatoes, often from temperate zone countries. Such importation can cause additional problems.

Especially, the import of seed potatoes is expensive. Dependence on imported seed tubers also creates a risk of introduction of pathogenic organisms from other countries. In addition, seed potatoes imported from temperate countries can only be grown in low highland temperatures. Such production

is often characterized by poor yield. It also contributes to soil erosion [16,20]. Therefore, it is necessary to look for strategies to reduce dependence on imported seed potato tubers and to improve the quality of domestic seed potatoes. New technologies are needed to support individual countries' efforts to be self-sufficient and to limit imports.

3. Aeroponic Production of Minitubers in Tropical and Subtropical Conditions

The modern system of producing high-quality seed potatoes should be based on using the adaptation potential of potato varieties to local growing conditions, such as resistance to high temperatures and droughts. Such a system must function in areas characterized by at least a low number of aphids which are virus-carrying vectors. Alternatively, seed potatoes should be produced under controlled conditions. It must also operate in an area free of soil-borne pathogens or use technological achievements of soil-less cultivation [5].

The introduction and development of rapid *in vitro* propagation techniques have shortened the time needed to produce a sufficiently large amount of basic seeds to as little as three years, counting from the first planting in the field. Those basic seeds are the basis for the production of certified seed potatoes, which are then sold to farmers for use in commercial production [10,25,26].

Pre-basic seed potatoes, or minitubers, are produced from *in vitro* plantlets and microtubers. The conventional production of minitubers usually takes place on solid substrates under controlled conditions. The production of minitubers is a classic way of multiplication and acclimatization of the *in vitro* material before its use in the open field [27].

The production of minitubers is a critical stage in the production of seed potatoes. The production of large quantities of high-quality minitubers, at low costs, in a relatively short amount of time and in an environmentally friendly manner is essential for the economically viable supply of seed potatoes and is a challenge in many countries [22].

An alternative production technique, which does not require soil or organic substrate, hydroponics, is based on aqueous solutions of minerals. The most commonly used hydroponic systems include Deep Flow Techniques (DFT) and Nutrient Film Techniques (NFT) [28]. In DFT systems, the root zone is completely submersed in the aerated nutrient solution. By contrast, the NFT system is based on the continuous flow of the nutrient solution in the growing root zone. Aeroponics stands out among the soil-less techniques, as it works very well in controlled greenhouse conditions [29]. In modern aeroponic constructions, the above-ground part of the plant develops similarly to soil crops while the roots hang down in the darkened part of the rhizotron, to which a solution of water and dissolved mineral nutrients is supplied in the form of fog or aerosol.

As noted by Gopinath et al. [30], such designs allow unrestricted growth of all parts of the plant. The first primitive devices for aeroponics were used by botanists to observe the root structure [26]. They quickly became an integral part of the potato seed production process in some regions.

Currently, aeroponics is recommended in seed potato production systems in temperate climate conditions. Among others, Ritter et al. [29] showed that its use for minituber production significantly improves yield. In the temperate climate, aeroponics is seen as a high yield potato multiplication system and is especially recommended for early and mid-season potato cultivars [31]. The use of aeroponic technologies on an industrial scale can enable the rapid production of large quantity of minitubers. It would reduce the length of the certified seed potato production program, widely accepted in Europe and Russia, from seven to four years [32].

Commercial production of seed potatoes using aeroponics is also developing in some tropical and subtropical regions, in countries like South Korea, China and India [30]. In India, the use of aeroponic technology is limited to the state of Punjab due to its high capital requirement and the 4-year period before any return is observed [18].

The aeroponic seed potato technology has been successfully used in some South American countries since 2006. At the International Potato Center (CIP) in Peru, a yield of 100 minitubers per plant has been achieved using relatively simple, publicly available materials in aeroponic constructions [33].

The 3G (three generations) seed strategy promoted by the CIP is based on the aeroponic production of large quantities of minitubers in one generation. The main goal of this strategy is to ensure the rapid production and delivery of high-quality seed potatoes to producers. It allows cost reduction compared to conventional production or other hydroponic techniques in Latin America. Seed potatoes are sold to small farmers who undergo appropriate training to re-use seed potatoes, e.g., with simple techniques such as positive selection and better storage. The 3G strategy has been adopted in some countries, such as Bolivia, Colombia, Peru and Ecuador. The use of aeroponic technology for the production of minitubers is currently being tested in several countries on the African continent, such as Ethiopia, Kenya, Uganda and Malawi (Table 3). Efforts are underway to incorporate aeroponics into the potato seed systems of some sub-Saharan African countries [22,30].

Table 3. Some tropic and subtropic countries with aeroponic installations used in the pre-basic seed potato production.

Region	Countries	References
South America	Bolivia	[22]
	Brazil	[16,21]
	Colombia	[22]
	Ecuador	[22]
	Peru	[22,33]
Sub-Saharan Africa	Ethiopia	[9,22,34]
	Kenya	[22,23,26]
	Malawi	[22,35]
	Uganda	[22,36]
Southeast Asia	Bhutan	[24]
	China	[37]
	India	[38]
	Indonesia	[20,39,40]

In Indonesia, potato production takes place in the highlands and often contributes to the deterioration of natural conditions, exacerbating soil erosion. The first aeroponic installations were introduced to support land protection in that country [20,39]. Kakuhenzire et al. [36] claimed that aeroponics has great potential for the production of large quantities of high-quality seed potatoes in highlands of many countries in the tropics. In addition, it has been shown that the application of a modified method of root zone cooling in the aeroponic system has allowed the expansion of the production area in wet lowland conditions. Therefore, despite the additional costs associated with the need to cool the root system, aeroponic cultivation is seen as a viable alternative in the production of high-quality seed potatoes in the lowlands of the tropics [20,39,40].

It should not be overlooked that work is underway to find a cheaper replacement for aeroponic seed production. Among others, advanced work on apical rooted cuttings is in progress in Vietnam and India [18]. In sub-Saharan Africa, cheaper solutions such as sand hydroponics are also sought. The advantages of this technology are that water and nutrients flow by gravity and the system does not require constant electricity supply. Although the initial and seasonal costs of sand hydroponics are lower, production rates are also lower than aeroponics [41]. In contrast, Thomas-Sharma et al. [12] see an increase in production and thus, the availability of high-quality seed potatoes in the informal system in the regions of the tropics and subtropics through improving the health status of seed tubers by integrating disease resistance and on-farm management tools with strategic seed replacement.

4. Advantages of Aeroponic Production of Minitubers

The amount of minitubers per plant produced in aeroponic cultivation is much higher than in conventional soil cultivation. It can achieve approximately 50–100 minitubers per plant, compared to 5–10, which is characteristic for soil production [26,33]. Using aeroponics, potato plants can yield

up to 250–300 minitubers per plant [42]. Preliminary results of the research of Kakuhenzire et al. [36] from Uganda have shown that aeroponic cultivation produces an average of 8.5 times more minitubers than conventional soil production. The number of minitubers per plant produced is directly reflected in the value of multiplication rates. Research by Mateus-Rodriguez et al. [22] showed that these multiplication rates are 1:45 and 1:6 for aeroponic and conventional production, respectively.

While comparing aeroponics to the other hydroponic system such as DFT, Chang et al. [43] showed that potato plants produce significantly more tubers per plant growing in a DFT system. However, the total tuber weight per plant is significantly higher in aeroponic systems. This is why aeroponics is the recommended approach when the production of larger tubers is desirable.

The multiple harvests that are possible in aeroponic production, as well as in other hydroponic systems, provide a higher yield compared to a single harvest of minitubers in soil production. Collecting minitubers that have reached the desired size enables the formation and growth of additional tubers harvested at later dates. The harvest is therefore extended in time and kept at specified intervals. Multiple harvestings of specific potato varieties can increase the number of harvested minitubers by 100–250% compared to a single harvest in soil cultivation [43,44]. In addition, systematic multiple harvests allow the production of large quantities of relatively uniform tubers of the desired size [43,45], which can also be marketed directly as seed potatoes [44].

The multiplication rates can also be increased by adjusting the nutrient composition [27]. In the aeroponic system, the nutrient composition is under complete control, which allows it to be adapted to the diverse needs of plants in different developmental phases as well as to the varieties grown and local conditions. Nutrients are delivered in the aeroponic system directly to the roots of the plants, which results in faster crop growth [30,46].

A higher yield can also be obtained by ensuring optimal root aeration in aeroponic production. A separate aeration system is not required [28,37]. In this respect, aeroponics is more advantageous than other hydroponic systems in which roots are immersed in an aqueous nutrient solution.

The healthiness of the produced seed potatoes is noteworthy. Aeroponic cultivation is devoid of many soil pathogens and physical or chemical properties of the soil adversely affecting the tubers. Thus, the number of damaged tubers is reduced. The high quality of the produced seeds is evident in the lack of infections and the physiological condition not differing from that of minitubers produced using other hydroponic structures [47].

Nowadays, when both soil and water are constantly shrinking resources in agriculture, man strives to produce more food per unit of soil and water [5]. Mateus-Rodriguez et al. [22] showed that the efficiency of aeroponic structures exceeds 900 minitubers per m², while the production of minitubers from in vitro plantlets in conventional systems allows the production of 300 minitubers per m².

The utilization of water used for aeroponic plant production can reach almost 99%. The advantage of this system is the recirculation of nutrient solution [30,34]. For comparison, it is worth adding that other variations of hydroponics may require twice the amount of water. However, the recirculation of the nutrient solution in soil-less systems can create favorable conditions for the development and spread of zoosporic microorganisms such as *Pythium* and *Phytophthora* spp. Therefore, it might be advisable to make use of some disinfection techniques or suppress the root pathogens with beneficial organisms [48,49].

Aeroponic production can be a closed production system in which not only the use of resources, but also environmental pollution is minimal [45].

By reducing the use of fertilizers by up to 60% and plant protection products by up to 100%, aeroponic plant cultivation contributes to environmental protection [50]. Wangchuk and Dochen [24] emphasized that aeroponics, by providing the exact amount of nutrients, reduces their wastage and minimizes the ingress of fertilizer residues into groundwater.

Aeroponic technology is promising for intensive seed potato production. In various countries, mass production of aeroponic cultivation equipment has begun, which can lead to a regular drop in its prices [51].

Aeroponics is also used in other potato production segments. It can, for example, diversify the offer of table potatoes by producing “Gourmet” potatoes for restaurant chains [45].

5. Aeroponic Production Deficiencies

In the continuous optimization of aeroponic production of minitubers, the specificity and requirements of the potato plant itself as well as the technical improvement of individual stages of production should be taken into account.

It is known that the potato tuberization phase is sensitive to the density of the solid substrate. The authors of [29] confirmed the delay in tuberization in the aeroponic production of minitubers, which could be due to the lack of mechanical stress acting on stolons.

In 2012, Banadysev pointed out the unjustified high costs of infrastructure and equipment as one of the reasons why soil-less seed potato production was not widespread [51]. Mbiyu et al. [26] and Mateus-Rodriguez et al. [22] also pointed out the high costs of launching aeroponic seed production. Calculations indicated that setting up a simple system capable of producing 80,000 minitubers a year costs around USD 24,000. In addition, aeroponic production of minitubers is labor-intensive and expensive due to manual plant care and manual harvesting. Service costs account for about 30% of the total costs incurred during one aeroponic production season.

On the other hand, Lakhiar et al. [50] have already emphasized that aeroponics compares favorably to other plant cultivation systems because it reduces labor costs. There is, therefore, still a need to understand the economics of minituber production using aeroponics [36].

The essential element determining the success of aeroponic structures is the composition of the nutrient solution. The authors of [44] suggested that success depends on meeting all requirements for the nutrient solution, such as appropriate temperature, electrical conductivity, pH and nutrient ratio that determine the growth of potato plants and the absorption of nutrients. Farran and Mingo-Castel [47] used the following composition of nutrient solution: KNO_3 (0.4 me/L), $\text{Ca}(\text{NO}_3)_2$ (3.1 me/L), NH_4NO_3 (4.4 me/L), KH_2PO_4 (4.4 me/L), MgSO_4 (1.5 me/L). The nutrient solutions should also contain microelements. The authors of [26] and [33] suggested adding Fe (EDTA-Fe 6%) and Petrilon combi that has the following formulation: 9% MgO, 3% S, 4% Fe, 4% Mn, 1.5% Cu, 1.5% Zn, 0.5% B, and 0.1% Mo. Carefully selected ingredients and parameters of the nutrient solution ensure the highest efficiency and quality and reduce susceptibility to biotic and abiotic stresses [34]. There may also occur nutrient deficiencies and toxicity during the production of minitubers because there are different requirements for different potato varieties. Therefore, as suggested by Farran and Mingo-Castel [47], a fully automatic system responsible for monitoring the composition and parameters of the nutrient solution is highly desirable.

The success of an aeroponic production system depends on a constant supply of electricity to the pump and circulation of the nutrient solution. Power fluctuation can damage the electronic equipment that controls the supply of nutrient solution to the rhizotron. Any loss of pump power can cause irreversible damage, including the complete loss of seedlings. It is known from practice that electrical power can be unreliable in many countries. Therefore, Kakuhenzire et al. [36] see the success of aeroponic production of minitubers in areas with access to a stable and affordable power supply. According to the authors, in many countries, diversification of energy sources and making use of renewable energy sources may be of key importance.

The lack of buffering capacity for water and chemicals in the system during power outages must be compensated by security systems (alarms, pumps), investment in infrastructure, advanced technology and a specialized producer organization. The use of aeroponics must be based on skilled labor [26,52].

Maintaining total darkness in the aeroponic chamber can be a problem since its sides are regularly opened to monitor root growth and to collect minitubers. Absolute darkness is necessary for tuber

formation as minimal light penetration transforms stolons into new stems [29]. In addition, light stimulates the production of glycoalkaloids. This fact is important in the production of ware potatoes. These compounds, at a high level of concentration and consumption, can be toxic to humans [45].

Adverse weather conditions, especially high temperatures, can also affect the efficiency of aeroponic seed production. In Malawi, the average yield of varieties used for experiments of Tsoka et al. [35] was 24.33 minitubers per plant and was lower than the potential yield (70 minitubers per plant) obtainable under aeroponic conditions. High temperature was indicated as a factor limiting yield in the areas of the tropics.

Aeroponic minituber production is favored by moderate temperatures. The ideal temperature should be 18–22 °C during the day and 14–18 °C at night [26]. In many countries, maintaining these temperatures in greenhouse conditions is a challenge. Cooling the nutrient solution, perhaps even with ice, may be required. These treatments increase the cost of producing minitubers, which results in more expensive seed potatoes [36].

There is insufficient knowledge about the shelf life of minitubers from aeroponic production during storage. Due to the special properties of the skin of minitubers produced in the aeroponic system, tuber dehydration under inadequate storage conditions may occur [31].

Farran and Mingo-Castel's studies [47] indicated that the physiological behavior of aeroponically produced minitubers is similar to those obtained by hydroponics. Despite this conclusion, the number of research results describing the field performance of minitubers produced in aeroponic systems is still insufficient. There is a need for a specific planting strategy for minitubers previously produced using aeroponic systems. Such minitubers harvested at different times may differ in dormancy at the next planting. The yield of such minitubers can be low and related to their small size [38,47]. In addition, the research results of Virtanen and Tuomisto [53] showed that the development and yield of minitubers produced in hydroponics was worse than those produced conventionally.

Some authors pointed out that traditional methods of plant protection against pests do not work well in aeroponic minituber production. Therefore, a new perspective is needed on the basis of a plant protection schedule adapted to the potato varieties and growing conditions [27,33,38,50].

Access to research results on the aeroponic production of minitubers in the tropics and subtropics is limited. Thus, the knowledge of potato growers in individual countries is also incomplete. There is often a lack of knowledge about the superiority of certified seeds and the availability and use of improved technologies in the production of seed potatoes. This leads to low yield in many countries. In Brazil, not many growers have decided to introduce an aeroponic system due to a lack of research and technical information. Several functioning systems operate without any scientific support. Potato growers require more training in growth, development and yielding of particular varieties in aeroponic cultivation and in maintaining the quality of seed tubers [11,16,34].

It is also important to comply with basic sanitary principles throughout the entire production process [24], which can be a challenge in the absence of a qualified or trained staff.

6. Final Considerations

Despite the fact that in many countries of the tropics and subtropics, the potato is now not only a staple food crop, but also a cash crop, its yield is still severely limited, most notably due to the shortage of high-quality seed potatoes. To satisfy the growing supply, seed potatoes are still grown for several generations in the field. This increases the risk of pathogen accumulation and transmission that leads to seed degeneration. The full potential of potato seeds is not being exploited.

A reasonable solution to the problem seems to be the use of an aeroponic production system that allows the reduction of the number of generations in the field to the necessary minimum and guarantees the elimination of soil-borne pathogens. The installation of such a system under controlled conditions also eliminates the presence of vectors that may spread pathogens. In these conditions, a large number of high-quality pre-basic seed potatoes can be produced.

The availability of large quantities of high-quality seed potatoes can reduce production costs and increase competitiveness of local production in relation to imported seeds. Private sector involvement can play a key role in this process. However, it is also worth considering that without a thorough economic assessment of aeroponic seed potato production systems in specific production areas, it cannot be used on a large scale by public or private entities.

Aeroponics may work in restricted areas as well as in areas where adverse environmental conditions, such as infertile soil or water scarcity, limit production. It seems that the increasing productivity per unit of soil surface should be a key factor to meet the growing demand for potatoes in the tropics and subtropics.

The growing role of public scientific institutions with significant research facilities can considerably increase the supply of high-quality seed potatoes using soil-less production of minitubers adapted to local conditions and local potato varieties. A more efficient knowledge and research results sharing process, as well as the exchange of experience, will help growers understand the advantages of aeroponic tuber production and overcome any potential difficulties.

The example of many countries (Table 3) shows that aeroponic installations may be a viable technological alternative in the pre-basic seed production in the tropics and subtropics. They create an opportunity to increase the production of seed potatoes and improve their health. However, further optimization of the production process is recommended by most of the authors. Adapting individual production parameters to climatic conditions, local realities and specific varieties is also recommended.

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