

# Potato production in aeroponics: An emerging food growing system in sustainable agriculture for food security

Mazhar H. Tunio<sup>1</sup>, Jianmin Gao<sup>1\*</sup>, Sher A. Shaikh<sup>1</sup>, Imran A. Lakhari<sup>1</sup>, Waqar A. Qureshi<sup>2</sup>, Kashif A. Solangi<sup>1</sup>, and Farman A. Chandio<sup>1</sup>

<sup>1</sup>Jiangsu University, School of Agricultural Equipment Engineering, 212013 Zhenjiang, P.R. China.

\*Corresponding author (gaojianminujs@163.com).

<sup>2</sup>Jiangsu University, Research Centre of Fluid Machinery Engineering and Technology, Zhenjiang, 212013 Jiangsu, P.R. China.

Received: 21 August 2019; Accepted: 9 December 2019; doi:10.4067/S0718-58392020000100118

## ABSTRACT

The global average potato (*Solanum tuberosum* L.) production is 17.4 t ha<sup>-1</sup>. Even using the same potato varieties, there is a large gap between higher yields and lower yields among countries. Potatoes are a cash crop and a significant part of the global diet. Therefore, low soil fertility, soil-borne diseases, poor water quality, and pests seriously affect potato production in developing countries. To improve potato quality and production, it is necessary for the modern world to improve its potato cultivation techniques. Aeroponics cultivation is an alternative technology of soilless culture for effectively adapting to areas of the world where soil and water are in critical condition. In aeroponic systems, plant roots are suspended in the open air under controlled circumstances to replace the soil with artificially provided foam or plastic stents. Moreover, the nutrient solution is spread through atomization nozzles. This review provides insights into the potential use of aeroponics in complementing potato production in developing countries. Moreover, in most developing countries, this technology should be adopted after deliberate consideration to increase potato production.

**Key words:** Aeroponics, nutrient solution, potato production, soilless culture, ultrasonic atomization.

## INTRODUCTION

The potato (*Solanum tuberosum* L.) is an annual crop in the genus *Solanum*, originated in the Andes near the border between Bolivia and Peru, South America. The potato was introduced to Europe from South America at the end of the 16<sup>th</sup> century, first entering Spain and then the United Kingdom. After the introduction of the potato to Europe, it moved from Europe to Asia and then the rest of the world (Harris, 1992). In 1596, Bauhin introduced the Latin name *Solanum tuberosum* for the species that was introduced in Europe, which was confirmed by Linnaeus in 1753. There are more than 230 wild potato species, including *S. ajanhuiri*, *S. curtilobum*, *S. xchaucha*, *S. goniocalyx*, *S. phureja*, *S. juzepczukii* and *S. stenotomum*, which are considered major potato species (Struik and Wiersema, 1999).

According to Beazell et al. (1939) and Chen et al. (2001), and a search of the US National Nutrition Database (USDA, 2015), the raw potato is an important source of antioxidants and contains 79% water, 22% dietary material, 325 kcal food energy, 7.6 g protein, 0.04 g fat, 72.8 g carbohydrates, 42 mg Ca, 231 mg P, 2.7 mg Fe, 70 IU vitamin A, 0.15 mg riboflavin, 4.4 mg niacin, and 64 mg ascorbic acid. Furthermore, the potato is one of the most important food crops (FAOSTAT, 2016), nutritious vegetables (Tibbitts et al., 1994), and is grown in different climate regions in many countries, including many temperate, tropical and subtropical regions (Fernie and Willmitzer, 2001).

Currently, the potato is the fourth-most important food crop in the world (Hancock et al., 2014; FAOSTAT, 2016), with a production of 377 million tons; the highest production is by China (22%), followed by India, Russia, Ukraine and USA (FAOSTAT, 2016). However, potato is the fourth-largest crop in China after wheat, rice, and corn (Zheng et al., 2016). Since 1993, China has been the world's largest potato producer (Wang and Zhang, 2004; Scott and Suarez, 2012). Furthermore, the report compiled by the US Department of Agriculture in Beijing revealed that China's fresh potato production in the 2017-2018 marketing year was estimated at 99 million tons, an increase of 5% from the previous year's estimated 92 million tons (Haytowitz and Pehrsson, 2018). The yield varies widely from region to region across China, which has four major potato producing regions; among these regions, Sichuan, Gansu, Guizhou, Yunnan and Inner Mongolia are the largest potato-producing provinces, accounting for approximately 60% of China's total fresh potato production. Industry sources have estimated that 60% of fresh potatoes are consumed via table consumption in homes and restaurants. Storage losses, the animal feed sector, the processing sector and seed potatoes account for approximately 5%, 20%, 10% and 4% of consumption of the harvest, respectively (USDA, 2015).

In recent years, potatoes have generally been more profitable than other crops in China, such as food crops, beans, oil crops, and cotton. It is not unusual for a potato crop producer to earn twice as much as they could if they grew another crop. Second, the potato processing industry is growing in China, and it requires more raw materials (Haytowitz and Pehrsson, 2018). Moreover, the country needs to develop cultivation techniques for improving the potato quality, for increasing production and for generating new varieties.

The average global production of potatoes is 17.4 t ha<sup>-1</sup>. USA is the most productive country, with an average of 44.2 t ha<sup>-1</sup>, and the UK is close behind. However, the average potato production in China is 14.35 t ha<sup>-1</sup> (FAOSTAT, 2016). There is a large gap between high and low yields between countries, even for the same potato varieties. The yield gap between farms in developing and developed economies represents a loss of opportunity of more than 400 million tons of potato crop production, depending on the crop varieties, seed age and quality, crop management practices and plant environment. Improvements in one or more of these yield determinants and the narrowing of the yield gap could contribute to the food supply and farmer incomes in developing countries (Thomas-Sharma et al., 2016; Lakhari et al., 2018a). Different methods have been developed for examining the physiology of tuberization as alternatives to using field-grown plants. These methods include the zone-separation method, in which the stolon and tuber zone formation is separated from soil and roots (Jaffé et al., 2014), cuttings, in vitro culture (Palmer and Smith, 1969; Perl-Treves and Galun, 1991), solution culture (Zheng et al., 2016), hydroponics (Wheeler and Tibbitts, 1989) and aeroponics (Lakhari et al., 2018a).

However, field farming is associated with significant risks and uncertainties in vital and non-biological stresses, such as high winds, floods, droughts, and pest attacks, because it requires more space for cultivation, high costs for preparing the land, labor and excess water. In this case, researchers looked for new agricultural techniques and reported that under a controlled environment, the proposed solution would be to implement techniques that are currently accessible. Soilless culture is one of these techniques.

Aeroponics is a modern technique for growing agricultural plants by providing a nutrient solution in the air without soil. Plant roots receive a nutrient spray mist from an atomizing nozzle (Lakhari et al., 2018a). Improved food production spaces and water-saving methods under soilless culture (Table 1) have led to promising results around the world (Sardare and Admane, 2013; Gruda, 2019). This approach uses relatively lower amounts of water input per unit of planted area, making it a safe and environmentally friendly way to grow plants (Ritter et al., 2001; Farran and Mingo-Castel, 2006) and control the rhizosphere (Buckseth et al., 2016). Shortly after its development, aeroponics became a valuable research tool and provided researchers with a non-invasive way to check the development of roots.

The aeroponic system is the best system for producing potatoes (Buckseth et al., 2016). Using this approach, plant roots can be quickly nourished under controlled conditions (Factor et al., 2007). These conditions include uniform nutrient concentrations, pH, EC, humidity, atomization spray time, atomization interval, atomization frequency, oxygen availability, temperature and light intensity (Lakhari et al., 2018a). However, plants grow rapidly in the growth chamber due to the disinfected environment and the availability of sufficient oxygen that improves potatoes in the aeroponic system (Calori et al., 2017).

To optimize the aeroponic system, many factors have been studied, such as ultrasonic effects (Lakhari et al., 2018b), root zone temperature, pH, water stress, N supply, electrical conductivity (EC) of nutrient solutions (Chang et al., 2012; Calori et al., 2017), nutrient disruption (Chang et al., 2008), plant density and harvest interval (Farran and Mingo-Castel,

**Table 1. List of crops that can be grown in soil-less culture (Sardare and Admane, 2013).**

Type of crops	Name of the crops
Cereals	<i>Oryza sativa</i> (rice), <i>Zea mays</i> (maize)
Fruits	<i>Fragaria xananassa</i> (strawberry)
Vegetables	<i>Lycopersicon esculentum</i> (tomato), <i>Solanum tuberosum</i> (potato), <i>Capsicum frutescens</i> (chili), <i>Solanum melongena</i> (brinjal), <i>Phaseolus vulgaris</i> (green bean), <i>Beta vulgaris</i> (beet), <i>Psophocarpus tetragonolobus</i> (winged bean), <i>Capsicum annuum</i> (bell pepper), <i>Brassica oleracea</i> var. <i>capitata</i> (cabbage), <i>Brassica oleracea</i> var. <i>botrytis</i> (cauliflower), <i>Cucumis sativus</i> (cucumber), <i>Cucumis melo</i> (melons), <i>Raphanus sativus</i> (radish), <i>Allium cepa</i> (onion)
Leafy vegetables	<i>Lactuca sativa</i> (lettuce), <i>Ipomoea aquatica</i> (kang kong)
Condiments	<i>Petroselinum crispum</i> (parsley), <i>Mentha spicata</i> (mint), <i>Ocimum basilicum</i> (sweet basil), <i>Origanum vulgare</i> (oregano)
Flower ornamental crops	<i>Tagetes patula</i> (marigold), <i>Rosa berberifolia</i> (roses), <i>Dianthus caryophyllus</i> (carnations), <i>Chrysanthemum indicum</i> (chrysanthemum)
Medicinal crops	<i>Aloe vera</i> (Indian aloe), <i>Solenostemon scutellarioides</i> (coleus)
Fodder crops	<i>Sorghum bicolor</i> (sorghum), <i>Medicago sativa</i> (alfalfa), <i>Hordeum vulgare</i> (barley), <i>Cynodon dactylon</i> (Bermuda grass), <i>Axonopus compressus</i> (carpet grass)

2006). Although aeroponics is becoming a special minitubers and high-quality potato production technology (Tierno et al., 2014), specific environments and specific potato cultivars still require optimized production techniques (Buckseth et al., 2016). Moreover, according to Chandra et al. (2014), compared to soil-grown plants, the aeroponics system has higher yields and comparable phenolic, flavonoid, and antioxidant properties.

This article is a literature review of potato production via aeroponic systems. We also discuss important considerations that should be addressed before establishing an aeroponic system for potato crops. Research areas are also provided to improve production and improve the field performance of potato crops that are produced aeroponically.

## POTATO SEED BREEDING AND PRODUCTION TECHNIQUES

There are many potato breeding techniques in the world for breeding seed potatoes, including conventional, micro-propagation, hydroponics, and aeroponics. However, for potato seed propagation, most farmers use the conventional methods of producing seed tubers in developing countries. Although all the methods have their limitations and challenges, traditional techniques have the greatest limitations in relation to producing high-quality seed potatoes under the conditions faced by under-resourced farmers.

### Conventional techniques

In the conventional system, seed potato tubers are commonly used for propagation and production (Struik and Wiersema, 1999). Tubers for harvesting and replanting in the field are called “seed potatoes”, as opposed to “potato seeds”. Due to their usual low reproductive rate of 1:6, using seed potatoes is very expensive, time-consuming, and takes many years to generate a large number of seed potatoes for potato producers and consumers (Otazú, 2010). This method has several drawbacks.

Crops propagated vegetatively, especially potatoes, are very sensitive to both bacterial and viral diseases. Traditional seed potato production contributes to the accumulation of disease, which greatly decreases crop yields (Badoni and Chauhan, 2010; El-Komy et al., 2010). During the growing season, if the mother plant is infected with a disease, each new tuber may also be infected. Moreover, seed potato growers discard poor quality seeds and must select higher quality, healthy tubers as seeds. Diseased and healthy plants are identified and isolated, and the healthy tubers are used for the next production season. The traditional method produces only approximately 8 tubers within 1 yr compared to other seed breeding methods (Otazú, 2010). This approach requires regular disease management through thermotherapy, which increases the incubation time and further increases the costs. To alleviate the bottleneck caused by this conventional multiplication method, a rapid seed potato multiplication technique has been used.

## Tissue culture

The science of cultivating plant organs, cells, or tissues on artificial media from the parent plant is known as tissue culture, and it is one of the new technologies leading to rapid daily proliferation. Tissue culture is very flexible and provides high expansion within a short period of time (Naik et al., 2000). Fast multiplication can solve some of the problems associated with the traditional propagation system (Struik and Wiersema, 1999). Fast multiplication provides seed potato tubers that lack seed-borne diseases (Jones, 1988).

Tissue culture has completely changed the seed potato production in some countries, such as Vietnam, which has doubled its potato yield and potato cropping area (Otroshy, 2006). Healthy plants can grow in the laboratory at any time of the year, and they are not limited by the weather or the time. Traditional cuttings and seedlings are not required, which saves much daily care.

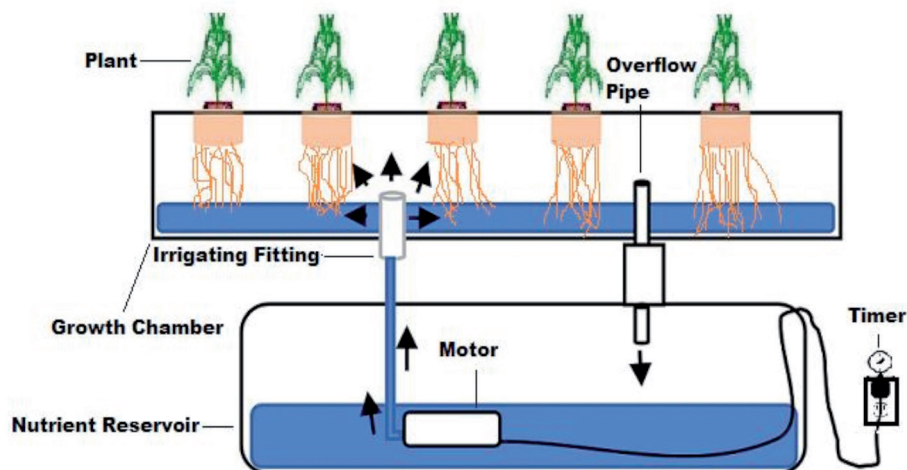
Tissue culture requires very expensive specialized equipment, most of which has a very high operating cost; for that reason, most developing countries do not promote this system. In addition, the different growth regulators used for making growth media, such as vitamins, energy, and nutrients, are very expensive (Badoni and Chauhan, 2010). After formal training, specialized skills and knowledge about tissue culture can be obtained. However, most countries do not have the capacity to conduct this specialized training, so the farmers in these countries continue engaging in less-sophisticated seed potato production. It is possible for 100% contamination to occur, especially when using materials grown in the field after insufficient sterilization. For commercially employed tissue culture, this phase must be performed at a low cost and a high survival rate. Tissue culture is also very expensive and time-consuming, especially in terms of reducing contamination (Shahsavari, 2010).

## Hydroponics

The term “hydroponics” comes from the Greek word “hydro” meaning water and “pónos” meaning labor. The hydroponic production of crops is characterized by propagation in solutions of water and nutrients, which can be set up with or without the addition of a growth medium to provide mechanical support to the plant’s root system (Resh, 2016). To provide physical support, natural or artificial plant media such as charcoal, rock wool, clay granules, peat moss, gravel or pots, sawdust, and coconut shells are sometimes used (Jones, 1988; Tierno et al., 2014) as shown in Figure 1.

Hydroponic systems are currently used for education, research, personal gardening, vegetables (tomatoes, potatoes, spinach, and lettuce), fruits (strawberries and cucumbers) and roses (Silberbush and Lieth, 2004; Nichols, 2006). The introduction of large-scale hydroponic systems for commercial mini-tuber production has provided an alternative method for studying potato physiology at the whole-plant level. Hydroponic systems described by (Wheeler et al., 2001) can support large numbers of plants in relatively cheap and easy-to-operate facilities. Hydroponic systems provide easy access to sample for physiological and anatomical studies and are therefore ideal for examining tuber initiation at the whole plant and organ levels (Jesse et al., 2019). Currently, various hydroponic systems have become available with

Figure 1. Schematic diagram of a hydroponic plant growing system.



the development of new materials and equipment. However, most hydroponic systems are operated automatically using controlled nutrients, lighting times and water volumes according to the needs of the plants (Resh, 2016).

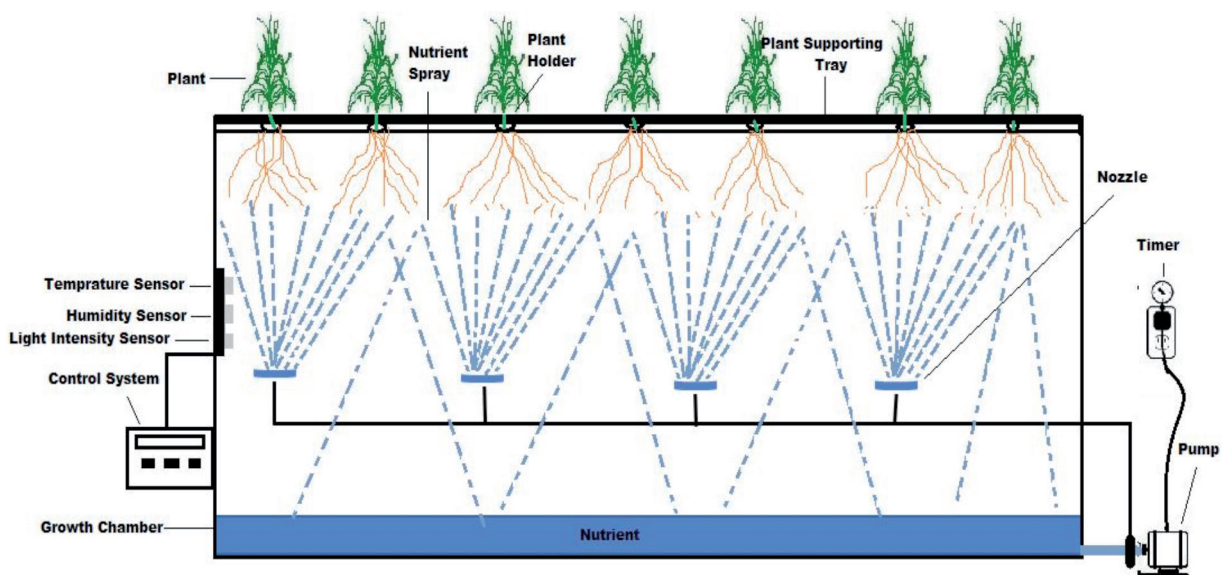
### Aeroponics system

Aeroponics is a technique that is more or less similar to hydroponics (Li et al., 2018). The only difference is that under aeroponics, plants are grown with the help of support and fine droplets (fog or aeroponic mist) of nutrient solution, and they do not need a single particle of soil or substrate to support the plants (Osvald et al., 2001; Lakhiar et al., 2018a; 2019). The term “aeroponic” is from the Latin “aero” meaning air and “póno” meaning works and is another method of soilless cultivation for growing plants in a controlled environment (Farran and Mingo-Castel, 2006), as shown in Figure 2. Aeroponics techniques allow for higher growth rates and healthy, uniform, and vigorous potato tubers. This can produce up to 10 times the yield of conventional production systems (Otaquí, 2010). Aeroponics techniques are credited for making potato production more efficient (Nichols, 2006), and can reduce the number of steps in the potato seed multiplication costs as well as plant health and quality of the first field.

### History of aeroponics

This soilless technique (aeroponics) was first introduced by botanists in the 1920s to study plant root structure, and for many years, aeroponics was used as a root physiology research tool (Barker, 1922). Facilitating root detection and cultivating plants in water vapor was first described by Carter. He concluded aeroponics is a valuable technique for cultivating plants, and it reduces mechanical damage and increases growth compared to soil and water culture. Klotz (1944) discovered a gaseous mist for citrus plants, and he was the first researcher to promote his research on citrus and avocado root diseases. In 1953, Vyvyan and Travell successfully planted apple plants in a foggy environment. Went (1957) planted tomato and coffee plants in a watertight container at Earhart Laboratories, Pasadena, California, with a fine nutrient fog propelled by a nebulizing syringe under pressure, naming the system “Aeroponics”. Before 1966, this system was only used as a laboratory analysis tool for studying plant root structure, and the system was exported from the laboratory in 1966 for commercial plant cultivation purposes (Stoner and Schorr, 1983). When the Disney Epcot Center opened in 1982, aeroponics attracted the attention of the public (Peterson and Krueger, 1988). Finally, in 1983, the first commercial aeroponics system was successfully launched and named the Genesis rooting system (Genesis Machine). The Genesis Machine can be operated and controlled by different types of microchips that are connected to power outlets and water atomizer nozzles. Peterson and Krueger (1988) noted in the comparison with other soilless culture techniques, only the aeroponic culture is more effective for use in plant culture, which can grow plants without interference from the soil. In addition, the researchers

Figure 2. Schematic diagram of an aeroponic system with automatic control.



also studied the response of root microorganisms to the drought legume-rhizobia interaction, arbuscular mycorrhizal fungi production and differences in the root growth of plant cultivars (Went, 1957; Tibbitts et al., 1994).

Barak et al. (1996) suggested that the nutrient fog system uses a minimum amount of water to provide a good environment for plant growth. However, NASA was also interested in promoting further research in aeroponics and applying it to grow plants in space. Researchers have noted crops cultivated in aeroponic systems are easier to harvest (Scoggins and Mills, 1998). However, some studies have addressed modern plant cultivation techniques for medicinal plants, roots-based herbs and the cultivation of ornamental horticultural plants (Burgess et al., 1998; Scoggins and Mills, 1998). It was concluded that in aeroponics system, plant roots are rapidly nourished under controlled conditions by the available nutrients. Martin-Laurent et al. (2000) and Blais et al. (1999) reported aeroponics is best for providing rich nutritional water around the roots of plants. Aeroponics technology tested in several African countries for the production of potato minitubers. Chang et al. (2012) stated aeroponics may be a suitable system for disrupting the nutrient supply for producing potato minitubers, and they concluded the stolon growth phase significantly increases root activity through restricted stolon growth. Therefore, overcoming non-tuber conditions such as high temperatures and late season varieties are beneficial for the use of this nutrient disruption technique. According to Lakhari et al. (2018a), aeroponics for plant cultivation is highly accepted and recommended in Europe and is currently practiced in Australia, Brazil, Singapore, France, Spain, Thailand, Japan, Russia, Malaysia, Germany, New Zealand, Egypt, South Korea, Indonesia, Bolivia, Colombia, Ecuador, Ethiopia, Mongolia, Peru, Uzbekistan, Kenya, Sri Lanka, Iran, Italy, Korea, Vietnam, Bhutan, Canada, Greece, Nigeria, India, Philippines, Poland, Abu Dhabi, Uganda, Tanzania, Mozambique, Malawi, Ghana, Ethiopia and Slovakia.

### **Overview of potato production in China**

Historically, Chinese farmers have planted a limited number of major crops, including rice and various grains. As early as the 17<sup>th</sup> century, the potato was first introduced by Dutch settlers to Taiwan (Bradshaw and Ramsay, 2009). Between 1949 and 1961, Chinese farms experienced structural changes, with farms underwrote into larger collective units of government land and with farmers being provided with more land. The government introduced these reforms to engage in collective agriculture and increase agricultural productivity. Despite these efforts, productivity has declined due to production constraints imposed by the government, such as the allocation of land for specific crops and the quota system for these crops. The decline in productivity has been coupled with drought and ineffective policy choices. After 1961, many policy adjustments occurred somewhere between relaxed and increased government control. Major changes began in 1978 when the production team was disbanded and collective farming was replaced with the Household Responsibility System (HRS). Under HRS, the land was still owned by communes, but farmers were allowed to make their own production decisions (Fan et al., 2007).

The introduction of HRS has led to a surge in potato production because demand is now driven by consumer preferences more than ever. As the market becomes more liberal, the ability to transfer potatoes to all parts of the country, especially from rural to urban areas, was critical to the growth of potato consumption. Until recently, potatoes were not widely consumed due to high transportation costs. In the early 1960s, when transport costs fell, potato production increased. The increase in Chinese potato production to 70% of the global potato production growth from 1961 to 2007 was attributed to China's growth (Wang and Zhang, 2010). Since 1993, China has led the world in both production and land area planted. China's potato production has grown due to rapid income growth and increased food consumption in the West, and demand continues to grow. In 2013, China produced 96 million tons of potatoes, while India, the second-largest producer, produced less than half that quantity, 45 million tons.

The increase in potato production is related to the introduction of HRS systems and the ability of farmers to meet consumer demand. Consumers have found that potatoes are an ideal vegetable, especially in winter, because they can be preserved for long periods and can be prepared in different ways (Wang and Zhang, 2010). To further increase consumer demand for potatoes further, the Chinese government is promoting potato production to improve food security and nutrient absorption. While demand is increasing, potato production is steadily increasing, leading to the increasing profitability of potato production (Jansky et al., 2009).

China's potato production is concentrated in four regions, namely the north, the middle, the southwest and the south, most of which is grown in the north and the southwest. The southwestern region of Yunnan accounts for approximately

40% of China's potato production. Furthermore, there are four growing seasons in Yunnan province, which is highly suitable for potatoes because it is cool at the end of spring and has plenty of rainfall and a high altitude (Jansky et al., 2009).

China's potato producers face major constraints that may hinder them from meeting growing consumer demand, including poor seed quality, disease and limited access to new technologies. In 2013, only China's demand for processed potatoes increased by 12% from the previous year. In 2015, the Chinese government began to promote potatoes as a potential new staple because potatoes can produce more food and more calories per unit of water than traditional staple crops such as rice and wheat. Therefore, potatoes are becoming a regular part of the Chinese diet.

### **Aeroponic system for potato production**

The aeroponic technique is an alternative method for soilless cultivation in controlled environments such as greenhouses. The system includes the supply of a nutrient solution to an enclosed root system with an atomizing device in a darkroom. Aeroponics systems primarily consist of electrical units, lightproof (dark) growth chambers, nutrient chambers, high-pressure pumps, filters, timers and nozzles (Buckseth et al., 2016).

### **Greenhouse**

For potato production, a normal greenhouse structure should provide a safe environment with minimal investments. This approach will allow us to reduce production costs, and plants should be protected from adverse factors and pests by a controlled climate (Riggio et al., 2019). The most common climate-limiting factor in greenhouses is heat. The lower roof of a greenhouse is basically warmer than the high roof, which must be covered with a sunshade/absorbance sheet to reduce its temperature. Fine mesh seals are applied to the roof, doors, and sides to prevent insects from falling off. The location of the greenhouse is also an important factor with respect to heat during the daytime. The floor of the greenhouse should be leveled properly for potatoes and related Solanaceae crops. Trees and buildings may not surround the greenhouse. However, electricity and power should be available (Otazú, 2010).

### **Source of water**

The source of water is also an important factor. Typically, chlorine (Cl) is used to treat drinking water. Cl and Na are two elements that significantly increase EC of water. In a conventional sense, Cl is generally harmless, but in aeroponics, if the concentration exceeds two parts per million, Cl is readily available to plants, is very harmful and may burn root tips. The water used in aeroponics should have a low EC, no more than 1 to 1.5 mS cm<sup>-1</sup>. Water sources with a pH above 8 are problematic for aeroponics (Otazú, 2010). The nutrient solution can be dispensed into the entire system using a 0.5-0.75 HP constant pressure pump (Mateus-Rodriguez et al., 2014). However, the pump may be installed according to the system's needs.

### **Power**

Operating an irrigation fertilization system requires power, with electricity as the primary source of power. A good generator with an automatic start-up system should be considered and ready at all times in case the general power fails. However, the plants could not survive, especially during the warmer days, without power for more than 1 h (Otazú, 2010).

### **Plant material**

The best plant materials are used in aeroponics, and due to hygienic reasons, *in vitro* plants are preferred (Wheeler and Tibbitts, 1986). However, experienced technicians are needed for the proper handling of plants. Plants of appropriate ages and sizes should undergo an acclimation period before being placed in the greenhouse (Buckseth et al., 2016). Furthermore, in an aeroponics system, aged and yellowish-colored plants may not be used. Moreover, plant materials should be free from diseases such as root cut up and tuber buds (Otazú, 2010).

### **Treatment of *in vitro* plants**

*In vitro* plants may be placed in a light environment immediately after growing in a test tube or magenta box. They can also be moved directly to the aeroponic boxes. However, according to Otazú (2010), due to insufficient root depth, a large number of plants die because they cannot absorb the nutrient solution. One day before the transplant, the magenta

box or test tube should be opened to expose the plants to the relative humidity of the greenhouse and to prevent exposure to direct sunlight at this time. From the first to fifth to seventh days, the plants may be watered with 1.1 diluted nutrient solutions. However, according to the environment in the greenhouse, only the necessary amount of water is required. The plants should be located to avoid direct sunlight exposure, with less watering or overwatering on the first day after transplantation. Thus, for these actions, the plants may be under unnecessary stress.

### **Growth boxes**

If the greenhouse facility is already available, the allocation of boxes should be performed in a way that optimizes the full space. The box distribution should be longitudinal or lateral. According to Otazú (2010), regarding the longitudinal distribution model, a plant density of 20 plants  $m^{-2}$  may be installed if there is an area of 80  $m^2$  or 12.4 plants  $m^2$  of greenhouse space. With the second allocation, an area of 162  $m^2$  with a 9.1 plants  $m^2$  may be installed for the plants. However, only one side window may have a longitudinal distribution pattern, which may lead to problems during harvesting for the operator, but the lateral distribution pattern with a window on both sides makes the harvest easier. The Styrofoam sheet is the most expensive item in the box structure, and it is not available in all the countries but has different sizes depending on the location. However, the box must be adjusted according to the size of the sheets. In distributing the plants in boxes, larger sized sheets are more convenient and will provide better results. Moreover, the most commonly available sizes of the sheets are  $3.0 \times 1.5 m^2$  and  $1.2 \times 2.4 m^2$ .

The aeroponics boxes require proper insulation, firmness, and solidity so that the roots of the plants may not be affected due to the temperature changes in the greenhouse. The wood or metal can be used to frame the box. However, wood is preferable due to its low cost and is always available all over the world. Styrofoam is the best, but if we provide the necessary moisture protection, compressed cardboard (ceiling) or compression sawdust can also work. All of these filler materials must be covered with opaque plastic, which is widely available in every part of the world (Otazú, 2010; Mbiyu et al., 2012).

### **Spray misters and droplet size**

In aeroponics systems, the roots of the plants receive a nutrient spray mist (Avvaru et al., 2006). The atomization is divided into high, medium and low-frequency atomization (Lu et al., 2009). The droplet sizes range from sub-microns to thousands of microns and are characterized by different classifications. The droplet size is categorized as a finely atomized mist of 10 to 100 microns from high pressure atomizing nozzles. The nozzles have holes measuring 0.635 mm (0.025 inches) and 0.4604 mm (0.016 inches) in operating pressure pumps of 551580.5832 and 689475.729 kPa (80-100 psi), and the ones that provide droplet sizes of 5-50 microns and 5-25  $\mu m$  are called spray misters (Lakhari et al., 2018a).

### **Ultrasonic atomization fogger**

Ultrasonic atomization is the phenomenon in which liquid in the form of a thin film on a vibrating surface (frequency  $\geq 20$  kHz) breaks into fine droplets (Avvaru et al., 2006). These foggers create the ideal artificial humidity in the air and insufficient humidity in a rainforest. The foggers are placed in the center of the container under a one-to-four-inch liquid solution and have a low cost. For successful plant growth, foggers improve the flow of oxygen to the roots while creating a suitable moist atmosphere (Lakhari et al., 2018b).

### **Pressure (airless and air spray) atomizing nozzle**

A fine spray that uses air to atomize the liquid is known as pressure atomization. In most cases, high-pressure air is supplied through the air compression vessel to operate the air-atomizing nozzle when small droplets are required. The droplet size depends on the operating frequency, and compacted air provides energy to break the larger liquid particles into very small-sized particles. The discharge of the nozzle depends on the liquid flow, the size of the spray head and the pressure pump, whereas the audible noise generated by the high-pressure nozzle is very high. A uniform water nutrient fog is precipitated directly to the root inside or above the chamber. The pressure nozzles are more convenient and easy to operate when a valve system is designed to lie within it (Lakhari et al., 2018b).



### **pH and EC measurements**

EC is the measure of the amount of electrical current a material can carry or its ability to carry a current. It is also known as specific conductance, with the symbol  $\sigma$ , and has the SI units of Siemens per meter ( $S\ m^{-1}$ ). The pH and EC of a nutrient solution can be easily measured with pH and EC meters. In this system, pH of the nutrient solution does not exceed 7.3 when water and the nutrients solution are recycled. Therefore, the ideal pH values are 6.5 to 6.8. However, the optimum EC values of the nutrient solution lie between 1.5 and 2.5  $dS\ m^{-1}$  (Calori et al., 2017). To replenish the nutrients and maintain correct pH and EC, the nutrient solution should be changed every 4 wk (Farran and Mingo-Castel, 2006; Mbiyu et al., 2012; Bag et al., 2015; Resh, 2016).

### **Temperature adjustment**

In aeroponic systems for rapid plant maturation, temperatures of the nutrient solution and air must be controlled (Menzel, 1983). The chemical process proceeds at a faster rate and deteriorates the enzyme activity when the temperature increases. During the daytime, temperature should not be higher than 30 °C or lower than 4 °C for a potato crop (Otazú, 2010). Moreover, for tuberization, optimum temperature during the daytime is up to 20 °C, and it is 10 ° to 15 °C during the nighttime.

### **Light**

For potato plants, light energy is an important environmental factor required for controlled cultivation. The light intensity and quality not only provide energy, but they also provide for a large number of morphogenesis and physiology-related responses during plant growth (Wheeler and Tibbitts, 1986; Fukuda et al., 2008; Li and Kubota, 2009). To adjust various light environments, light-emitting diodes (LEDs) have become popular as new light sources in aeroponic systems. A study by Mori et al. (2002) reported high photosynthesis and growth rates of plants grown under LEDs. In aeroponic systems, LEDs can be considered as the best light, and they provide a variety of light qualities for plant growth. However, optical LEDs have longer lifetimes (Cio'c et al., 2019). They are energy savers with a narrow band, a single wavelength, and lower mass and volume (Brown et al., 1995).

### **Humidity**

For successful plant growth and development, humidity is a major factor in aeroponic systems. However, increases and decreases in the relative humidity seriously affect plant growth (Schussler, 1992). Humidity affects the physiological functions of plants and causes disease problems. Moreover, it is very convenient to control and maintain humidity in the growth chamber on a regular basis.

### **Timers**

There may be a timer that can be calibrated every 10 s, after 10 min (Farran and Mingo-Castel, 2006). However, Liu et al. (2018) used a calibration timer to make the system functional 10 s after every 20 min for potato crops. Moreover, according to Otazú (2010), to manage the system during the day and on cool nights, simply activating the system for 15 min after every 15 min and 15 min per hour, respectively, is needed to keep it active.

### **Nutrient solution**

The different nutrient solutions required by each potato grower depend on the water quality, the chemical used in the preparation of the nutrient solution and the varieties (Bag et al., 2015). When nutrients may have added to the water, EC will definitely increase. In general, if we want to avoid phytotoxicity problems, EC should not exceed 2.0  $mS\ cm^{-1}$ . Fertilizers that contain Cl or Na may not be used, and moreover, fertilizers that are good contributors to the EC are N and K. Plants need macronutrients (N, P, K, Ca, and Mg) and micronutrients (Mn, Cu, Zn, B, S, Mo and Fe), which may be dissolved in water so that the plants can absorb them through their roots for normal growth.

In aeroponics, previously tested fertilizers should be used for potato production as presented in Table 2.

**Table 2. Nutrient solutions used for aeroponic potato production.**

Farran and Mingo-Castel, 2006; Mbiyu et al., 2012		Otazú, 2010	
Nutrient	Concentration (%)	Nutrient	Concentration (%)
KNO <sub>3</sub>	0.4	KNO <sub>3</sub>	5.4
Ca(NO <sub>3</sub> ) <sub>2</sub>	3.1	NH <sub>4</sub> NO <sub>3</sub>	4.4
NH <sub>4</sub> NO <sub>3</sub>	4.4	Ca superphosphate	2.6
KH <sub>2</sub> PO <sub>4</sub>	4.4	MgSO <sub>4</sub>	1.0
MgSO <sub>4</sub>	1.5	Fe (EDTA-Fe 6%)	0.05
		B (boric acid)	0.001
		Micro (Fetrilon*)	0.009
	pH 5.7		pH 6.5

\*The formulation of Fetrilon combi: S 3%, MgO 9%, Cu 1.5%, Mn 4%, Fe 4%, B 0.5%, Zn 1.5% and Mo 0.1% is a commercial foliar micronutrient powder.

### Nutrient preparation for potato crops

For a 400 L nutrient solution for a potato crop, Table 3 provides the complete information.

Ca superphosphate is not soluble in water, unlike other nutrients, so a small amount of water is added until all the nutrients are completely dissolved. Initially, during the first few days, a nutrient solution of only 100 L is prepared, and water is added to reach a volume of 200 L (50% strength). However, the solution with a final volume of 400 L at full strength should be applied after the second week. The appearance of any toxic symptoms in the leaves indicates that the nutrient solution should be frequently replaced to avoid incompatibility with the plant. The pH of nutrient solution and water is also convenient to check. The optimal pH 5.5 to 6 provides maximum nutrient availability for plants (Calori et al., 2017), and if it exceeds 7.3, it can be reduced with a diluted phosphoric acid or sulfuric acid solution (Otazú, 2010; Resh, 2016).

**Table 3. Nutrients required for a potato aeroponic module of 400 L.**

Nutrient	meq L <sup>-1</sup>	g L <sup>-1</sup>	g 400 L <sup>-1</sup>	Nutrient	meq L <sup>-1</sup>	g L <sup>-1</sup>	g 400 L <sup>-1</sup>
K Nitrate	5.4	0.54	216	Mg Sulfate	1.000	0.240	96.0
NH <sub>4</sub> Nitrate*	4.4	0.35	140	Fetrilon combi	0.034	0.009	4.8
Ca triple superphosphate	2.6	0.28	112	Iron chelate (6%)	0.050	0.012	3.6

\*When tuberization is initiated, the concentration should be reduced by half after 2-mo of transplantation.

### Quality control

For virus indexing, enzyme-linked immunosorbent assay (ELISA) tests may be conducted, and leaf samples may be collected from the plants. Moreover, at least two tests should be performed after 1 mo and 2 to 3 mo after transplantation (Mbiyu et al., 2012).

### Harvest and handling of minitubers

Early maturing potato varieties begin to produce minitubers after 2 wk of transplanting. When the minitubers reach at least 8 g or are equivalent to 0.5 cm in diameter, it is best to harvest them when it is cool in the morning (Otazu, 2014). However, Mateus-Rodriguez et al. (2014) removed all the minitubers with a diameter greater than 1.5 cm during the first harvest to enhance the start of more tubers. After every 10 to 14 d, subsequent harvests may be performed. The harvest lasts until the plant reaches approximately 6 mo old (Mbiyu et al., 2012).

### PRODUCTION ADVANTAGES OF POTATOES IN AEROPONIC SYSTEMS

The use of aeroponics for more production under specific temperature conditions greatly increased the yield (Ritter et al., 2001). Furthermore, Farran and Mingo-Castel (2006) reported that the potato yield was 800 tubers m<sup>2</sup> when harvested on a weekly basis over a 5-mo period. However, the multiplication rate was 1:13. At the International Potato Center (CIP) in Peru, yields of more than 100 tubers plant<sup>-1</sup> were obtained (Otazú, 2010). In optimizing tuber production, the harvest timing was a key factor (Ewing and Wareing, 1978). Compared to traditional hydroponics, aeroponics optimizes the root

changes and limits water usage, and EC and pH monitoring and solution recirculation are key factors in changing the yield growth (Soffer and Burger, 1988). Blais et al. (1999) and Vintal et al. (1999) concluded that aeroponic technology has been successfully applied to ornamental species, vegetables, and potato crop production.

### **ECOLOGICAL FACTORS OF POTATO CROPS IN RELATION TO AEROPONICS**

The production of natural and healthy potato plants in an aeroponic system is considered safe and eco-friendly, and the water and energy input per unit area is also low. However, a limited amount of water is used due to the recycling of the nutrient solution in this system (Ritter et al., 2001; Farran and Mingo-Castel, 2006). The aeroponic system provides crops with their precise plant nutrient requirements, minimizing the risk of fertilizer residues entering the water table and reducing fertilizer use (Nichols, 2006). However, all these findings clearly show that this system is a research tool for nutrient absorption and optimizing crops and introduces possibilities for monitoring plant health in enclosed environments. Because of the reduced interplant contact, the environment under aeroponics is not affected by pests and diseases; plants are healthier and grow faster than plants grown in traditional culture systems (Tibbitts et al., 1994; Salisbury and Clark, 1996; Waters et al., 2002). Without destroying or infecting other plants, a diseased plant will be removed quickly from the plant support structure. Additionally, compared to traditional forms of cultivation such as soil and hydroponics, plants can grow at a higher density (Stoner and Schorr, 1983).

### **ADVANTAGES OF AEROPONIC SYSTEMS**

The most relevant advantages of aeroponics compared to traditional agriculture are as follows:

- Aeroponic systems use a very small amount of water for potato field production, at 1/10 to 1/30 the amount. In desert areas such as Saudi Arabia, aeroponics has achieved commercial success.
- Independent of soil quality and land, aeroponics provides for successful agriculture. Moreover, the soil is never used during the process because the soil composition is irrelevant.
- Limited land area and outcome: aeroponics has the highest yield per unit area per year for all known systems due to its three-dimensional growth system.
- Greenhouses may be built around city centers and markets to reduce cargo and provide consumers with fresh products.
- Production has nothing to do with any seasonal adverse effects, such as hot, dry, cold or windy weather. The crop can be planted all year round. The growing season is extended, so the yield is higher.
- Within a shorter period, this approach produces disease-free potatoes in higher quantities.
- The cost of planting potato crops with aeroponics is approximately one-quarter that of traditionally grown crops.
- There is no need to sterilize the growth medium to minimize cost. There are no any systems designed for soil diseases, weeds and nematodes. The entire aeroponic system provides a uniform supply of water to plants.
- Closer plant spacing can be achieved, and mobile plant channels can provide greater yields for the same area for certain crops.
- Mini potatoes can be harvested in any size (5 to 30 g) that the user wants.
- Fertilizer is sprayed directly on the roots so that the growth phase can last for more than 180 d without interruption, which is not a problem in aeroponic techniques.
- The initiation of new tubers causes higher yields due to the removal of major tubers.

### **DISADVANTAGES OF AEROPONICS SYSTEMS**

- It is costly to engage in production for longer times.
- Growers need the appropriate knowledge and a specific level of proficiency to operate the system supplying the nutrients needed for plant growth.
- It is important to provide nutrients at the desired concentrations. If there is an oversupply, plants will die, and no solid culture can absorb excess nutrients.
- The system design materials are sometimes expensive. Because of the well-designed system, advanced equipment is required. This equipment primarily consists of a constant-pressure high-pressure pump, an atomizing nozzle, equipment for controlling the humidity and light intensity, a temperature sensor, a timer to control the system, and EC and pH measuring devices.

## **WHAT WE RECOGNIZE AND WHAT REMAINS TO BE RECOGNIZED IN AEROPONICS SYSTEM**

Today's farming demands more efficiency, so more sophisticated technology is required. The initial experiments revealed the following information about aeroponics. Because it is a new technology, more study on this system is needed. In aeroponic systems, the initial investment can be recovered rapidly, from the significant reduction in the production cost of high-quality potatoes, and it is more accessible to growers but sensitive to the climate. Non-conventional sources of energy (wind and solar) also seem to be compatible with this system. However, many factors need to be tested, such as the planting intervals for each breed. In vitro plants have been shown to produce good yields in aeroponic systems. Tuber stems and minitubers also need to be compared and identified for other plant materials. The best production season requires the identification of each location based on the weather and the on-site production season. The effect of manually extracting plants after each harvest (as a way to increase the formation of new stones and tubers) on the total production should be studied. Economic assessments must also be performed to determine the feasibility of the system. Solar/wind energy should be used to overcome high energy costs and ensure the need for the commercial use of normal electricity supplies. The nutrient solution for each variety must be investigated because different varieties may require different optimum nutrient solutions. Pest and disease control must be optimized because they are different from the methods encountered in field potato production. Finally, it is important to study the nozzle type, droplet size of the atomizer and the best nozzle frequency for potato crops, which is the most urgent topic for future study.

## **FUTURE PROSPECTS**

Compared to traditional methods or other soilless cultures such as hydroponics (water growth), this method has the potential to reduce costs and improve production. In a relatively short period of time, aeroponics systems have been used in many cases from outdoor field farming to indoor greenhouse farming. Aeroponic systems can be used for intensive food production in limited areas where fresh water and fertile soil are not available and will be effectively used in developing countries at the same time. In the future, aeroponics will be effectively used in many areas. Therefore, in the areas with most of the non-cultivable land, small areas and large populations, and desert areas, aeroponics may be a potential application for food production.

## **CONCLUSIONS**

As discussed in this review, the aeroponics system appears to be the best system for potato production, an emerging food growing system in sustainable agriculture for food security, especially in areas where soil and water are in critical condition. The system significantly increases potato production compared with the other systems currently in use and also provides protection from pests and soil-borne diseases. Given the potential advantages of the aeroponics system, such as its good nutrition monitoring and fast seed production, capacity to improve seedling survival rates and growth, spacious area, constant air circulation and eco-friendly nature, this system has the potential to reform the potato production industry. Furthermore, in the case of insufficient natural sources, the aeroponics system can be used effectively for the production of other vegetables in various countries.

## **ACKNOWLEDGEMENTS**

We acknowledged that this work was financially supported by the National Natural Science Foundation of China Program (Nr 51975255), Jiangsu Agriculture Science and Technology Innovation Funds (JASTIF), (CX (18) 3048), and the "Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (Nr 37, 2014).

## **REFERENCES**

- Avvaru, B., Patil, M.N., Gogate, P.R., and Pandit, A.B. 2006. Ultrasonic atomization: effect of liquid phase properties. *Ultrasonics* 44(2):146-158.
- Badoni, A., and Chauhan, J. 2010. Conventional vis-a-vis biotechnological methods of propagation in potato: A review. *Stem Cell* 1(1):1-6.

- Bag, T., Srivastava, A., Yadav, S., Gurjar, M., Diengdoh, et al. 2015. Potato (*Solanum tuberosum*) aeroponics for quality seed production in north eastern Himalayan region of India. *Indian Journal of Agricultural Science* 85(10):1360-1364.
- Barak, P., Smith, J., Krueger, A., and Peterson, L. 1996. Measurement of short-term nutrient uptake rates in cranberry by aeroponics. *Plant, Cell and Environment* 19(2):237-242.
- Barker, B. 1922. Studies on root development. Long Ashton Research Station Annual Report 1921:9-57.
- Beazell, J., Schmidt, C., and Ivy, A. 1939. On the digestibility of raw potato starch in man. *Journal of Nutrition* 17:77-83.
- Blais, J., Dufresne, S., et Mercier, G. 1999. État du développement technologique en matière d'enlèvement des métaux des effluents industriels. *Revue des Sciences de l'Eau* 12(4):687-711.
- Bradshaw, J.E., and Ramsay, G. 2009. Potato origin and production. p. 1-26. In Singh, J., Kaur, L., Singh, J., and Kaur, L. (eds.) *Advances in potato chemistry and technology*. Academic Press, Elsevier, Cambridge, Massachusetts, USA.
- Brown, C.S., Schuerger, A.C., and Sager, J.C. 1995. Growth and photomorphogenesis of pepper plants under red light-emitting diodes with supplemental blue or far-red lighting. *Journal of the American Society for Horticultural Science* 120(5):808-813.
- Buckseth, T., Sharma, A., Pandey, K., Singh, B., and Muthuraj, R. 2016. Methods of pre-basic seed potato production with special reference to aeroponics - A review. *Scientia Horticulturae* 204:79-87.
- Burgess, T., McComb, J., Hardy, G., and Colquhoun, I. 1998. Influence of low oxygen levels in aeroponics chambers on eucalypt roots infected with *Phytophthora cinnamomi*. *Plant Disease* 82(4):368-373.
- Calori, A.H., Factor, T.L., Feltran, J.C., Watanabe, E.Y., de Moraes, C.C., et al. 2017. Electrical conductivity of the nutrient solution and plant density in aeroponic production of seed potato under tropical conditions (winter/spring). *Bragantia* 76(1):23-32.
- Chandra, S., Khan, S., Avula, B., Lata, H., Yang, M.H., et al. 2014. Assessment of total phenolic and flavonoid content, antioxidant properties, and yield of aeroponically and conventionally grown leafy vegetables and fruit crops: A comparative study. *Evidence-Based Complementary and Alternative Medicine* 2014:ID2538752. <http://dx.doi.org/10.1155/2014/2538752>.
- Chang, D.C., Park, C.S., Kim, S.Y., Kim, S.J., and Lee, Y.B. 2008. Physiological growth responses by nutrient interruption in aeroponically grown potatoes. *American Journal of Potato Research* 85(5):315.
- Chang, D.C., Park, C.S., Kim, S.Y., and Lee, Y.B. 2012. Growth and tuberization of hydroponically grown potatoes. *Potato Research* 55(1):69-81.
- Chen, J., Huang, Y., and Caldwell, R.D. 2001. Best management practices for minimizing nitrate leaching from container-grown nurseries. *The Scientific World Journal* 1:96-102.
- Cio'c, M., Kalisz, A., Zupnik, M., and Pawlowska, B. 2019. Different LED light intensities and 6-benzyladenine concentrations in relation to shoot development, leaf architecture, and photosynthetic pigments of *Gerbera jamesonii* Bolus in vitro. *Agronomy* 9(7):16.
- El-Komy, M.H., Abou-Taleb, E.M., Aboshosha, S.M., and El-Sherif, E.M. 2010. Differential expression of potato pathogenesis-related proteins upon infection with late blight pathogen: a case study expression of potato osmotin-like protein. *International Journal of Agriculture and Biology* 12(2):179-186.
- Ewing, E.E., and Wareing, P.F. 1978. Shoot, stolon, and tuber formation on potato (*Solanum tuberosum* L.) cuttings in response to photoperiod. *Plant Physiology* 61(3):348-353.
- Factor, T.L., Araujo, J.A.C., Kawakami, F.P.C., e Junck, V. 2007. Produção de minituberculos basicos debatata em tres sistemas hidroponicos. *Horticultura Brasileira* 25(1):82-87.
- Fan, S., Gulati, A., and Dalafi, S. 2007. Overview of reforms and development in China and India. p. 10-48. *The dragon and the elephant: Agricultural and rural reforms in China and India*. The Johns Hopkins University Press for International Food Policy Research Institute (IFPRI), Baltimore, Maryland, USA.
- FAOSTAT. 2016. Agriculture Organization of the United Nations Statistics Division. Economic and Social Development Department, FAO, Rome, Italy. Available at <http://faostat3.fao.org/home/E>.
- Farran, I., and Mingo-Castel, A.M. 2006. Potato minituber production using aeroponics: effect of plant density and harvesting intervals. *American Journal of Potato Research* 83(1):47-53.
- Fernie, A.R., and Willmitzer, L. 2001. Molecular and biochemical triggers of potato tuber development. *Plant Physiology* 127(4):1459-1465.
- Fukuda, N., Fujita, M., Ohta, Y., Sase, S., Nishimura, S., et al. 2008. Directional blue light irradiation triggers epidermal cell elongation of abaxial side resulting in inhibition of leaf epinasty in geranium under red light condition. *Scientia Horticulturae* 115(2):176-182.
- Gruda, N. 2019. Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. *Agronomy* 9:298. doi:10.3390/agronomy9060298.
- Hancock, R.D., Morris, W.L., Ducreux, L.J., Morris, J.A., Usman, M., et al. 2014. Physiological, biochemical and molecular responses of the potato (*Solanum tuberosum* L.) plant to moderately elevated temperature. *Plant, Cell and Environment* 37(2):439-450.
- Harris, P. (ed.) 1992. Mineral nutrition. p. 162-213. *The potato crop. The scientific basis for improvement*. Springer, Dordrecht, The Netherlands.

- Haytowitz, D.B., and Pehrsson, P.R. 2018. USDA's National Food and Nutrient Analysis Program (NFNAP) produces high-quality data for USDA food composition databases: Two decades of collaboration. *Food Chemistry* 238:134-138.
- Jaffé, Y.L., Aragón-Salamanca, A., Ziegler, B., Kuntschner, H., Zaritsky, D., et al. 2014. Ionized gas discs in elliptical and S0 galaxies at  $z < 1$ . *Monthly Notices of the Royal Astronomical Society* 440(4):3491-3502.
- Jansky, S., Jin, L., Xie, K., Xie, C., and Spooner, D. 2009. Potato production and breeding in China. *Potato Research* 52(1):57.
- Jesse, S., Zhang, Y., Margenot, A.J., and Davidson, P.C. 2019. Hydroponic lettuce production using treated post-hydrothermal liquefaction wastewater (PHW). *Sustainability* 11:3605. doi:10.3390/su11133605.
- Jones, E.D. 1988. A current assessment of in vitro culture and other rapid multiplication methods in North America and Europe. *American Potato Journal* 65(4):209-220.
- Klotz, L. 1944. A simplified method of growing plants with roots in nutrient vapors. *Phytopathology* 34:507-508.
- Lakhiar, I.A., Gao, J., Syed, T.N., Chandio, F.A., and Buttar, N.A. 2018a. Modern plant cultivation technologies in agriculture under controlled environment: A review on aeroponics. *Journal of Plant Interactions* 13(1):338-352.
- Lakhiar, I.A., Gao, J., Xu, X., Syed, T.N., Chandio, F.A., Jing, Z., et al. 2019. Effects of various aeroponic atomizers (droplet sizes) on growth, polyphenol content, and antioxidant activity of leaf lettuce (*Lactuca sativa* L.) *Transactions of the ASABE* 62(6):1475-1487. doi:10.13031/trans.13168.
- Lakhiar, I.A., Jianmin, G., Syed, T.N., Chandio, F.A., Buttar, N.A., et al. 2018b. Monitoring and control systems in agriculture using intelligent sensor techniques: A review of the aeroponic system. *Journal of Sensors* 2018:ID8672769. <https://doi.org/10.1155/2018/8672769>.
- Li, Q., and Kubota, C. 2009. Effects of supplemental light quality on growth and phytochemicals of baby leaf lettuce. *Environmental and Experimental Botany* 67(1):59-64.
- Li, Q., Li, X., Tang, B., and Gu, M. 2018. Growth responses and root characteristics of lettuce grown in aeroponics, hydroponics, and substrate culture. *Horticulturae* 4:35. doi:10.3390/horticulturae4040035.
- Liu, X., Wang, G., and Gao, J. 2018. Experimental study of ultrasonic atomizer effects on values of EC and pH of nutrient solution. *International Journal of Agricultural and Biological Engineering* 11(5):59-64.
- Lu, X., Yang, S., and Evans, J.R. 2009. Microfeeding with different ultrasonic nozzle designs. *Ultrasonics* 49(6-7):514-521.
- Martin-Laurent, F., Tham, F.-Y., Lee, S.-K., He, J., and Diem, H.G. 2000. Field assessment of aeroponically grown and nodulated *Acacia mangium*. *Australian Journal of Botany* 48(1):109-114.
- Mateus-Rodríguez, J., de Haan, S., and Rodríguez-Delfín, A. 2014. Genotype by environment effects on Potato mini-tuber seed production in an aeroponics system. *Agronomy* 4(4):514-528.
- Mbiyu, M., Muthoni, J., Kabira, J., Elmar, G., Muchira, C., et al. 2012. Use of aeroponics technique for potato (*Solanum tuberosum*) minitubers production in Kenya. *Journal of Horticulture and Forestry* 4:172-177. <https://dx.doi.org/10.5897/JHF12.012>.
- Menzel, C. 1983. Tuberization in potato at high temperatures: interaction between shoot and root temperatures. *Annals of Botany* 52(1):65-69.
- Mori, Y., Takatsujt, M., and Yasuoka, T. 2002. Effects of pulsed white LED light on the growth of lettuce. *Journal of Society of High Technology in Agriculture* 14(3):136-140.
- Naik, P., Chakrabarti, S., Sarkar, D., and Birhman, R. 2000. Potato biotechnology: Indian perspective. p. 194-211. *Indian Potato Association*, Shimla, India.
- Nichols, M. 2006. Berry fruit in Belgium. *Practical Hydroponics and Greenhouses* 90:41-46.
- Osvald, J., Petrovic, N., and Demsar, J. 2001. Sugar and organic acid content of tomato fruits (*Lycopersicon lycopersicum* Mill.) grown on aeroponics at different plant density. *Acta Alimentaria* 30(1):53-61.
- Otazú, V. 2010. Manual on quality seed potato production using aeroponics. p. 44. Available at <http://cippotato.org/research/publication/manual-on-quality-seed-potatoproduction-using-aeroponics>. International Potato Center (CIP), Lima, Peru.
- Otroshy, M. 2006. Utilization of tissue culture techniques in a seed potato tuber production scheme. Wageningen University, Wageningen, The Netherlands.
- Palmer, C., and Smith, O. 1969. Cytokinins and tuber initiation in the potato *Solanum tuberosum* L. *Nature* 221(5177):279.
- Perl-Treves, R., and Galun, E. 1991. The tomato Cu, Zn superoxide dismutase genes are developmentally regulated and respond to light and stress. *Plant Molecular Biology* 17(4):745-760.
- Peterson, L.A., and Krueger, A.R. 1988. An intermittent aeroponics system. *Crop Science* 28(4):712-713.
- Resh, H.M. 2016. *Hydroponic food production: A definitive guidebook for the advanced home gardener and the commercial hydroponic grower*. CRC Press, Boca Raton, Florida, USA.
- Riggio, G., Jones, S.L., and Gibson, K.E. 2019. Risk of human pathogen internalization in leafy vegetables during lab-scale hydroponic cultivation. *Horticulturae* 5:25. doi:10.3390/horticulturae5010025.
- Ritter, E., Angulo, B., Riga, P., Herran, C., Relloso, J., et al. 2001. Comparison of hydroponic and aeroponic cultivation systems for the production of potato minitubers. *Potato Research* 44(2):127-135.
- Salisbury, F.B., and Clark, M.A. 1996. Choosing plants to be grown in a controlled environment life support system (CELSS) based upon attractive vegetarian diets. *Life Support and Biosphere Science* 2(3-4):169-179.
- Sardare, M.D., and Admane, S.V. 2013. A review on plant without soil-hydroponics. *International Journal of Research in Engineering and Technology* 2(03):299-304.

- Schussler, W. 1992. The influence of different constant and fluctuating water vapor pressure gradients on morphogenesis. *Acta Horticulturae* 327:105-110.
- Scoggins, H.L., and Mills, H.A. 1998. Poinsettia growth, tissue nutrient concentration, and nutrient uptake as influenced by nitrogen form and stage of growth. *Journal of Plant Nutrition* 21(1):191-198.
- Scott, G.J., and Suarez, V. 2012. Limits to growth or growth to the limits? Trends and projections for potatoes in China and their implications for industry. *Potato Research* 55(2):135-156.
- Shahsavari, E. 2010. Evaluation and optimizations of media on the tissue culture system of upland rice. *International Journal of Agriculture and Biology* 12(4):537-540.
- Silberbush, M., and Lieth, J. 2004. Nitrate and potassium uptake by greenhouse roses (*Rosa hybrida*) along successive flower-cut cycles: a model and its calibration. *Scientia Horticulturae* 101(1-2):127-141.
- Soffer, H., and Burger, D.W. 1988. Effects of dissolved oxygen concentrations in aero-hydroponics on the formation and growth of adventitious roots. *Journal of the American Society for Horticultural Science* 113(2):218-221.
- Stoner, R., and Schorr, S. 1983. Aeroponics versus bed and hydroponic propagation [The process of propagating and growing plants in air]. *Florists' Review (USA)*. *Florists Review* 173(4477):1-2.
- Struik, P.C., and Wiersema, S.G. 1999. Seed potato technology. Wageningen Academic Publishers, Wageningen, The Netherlands.
- Thomas-Sharma, S., Abdurahman, A., Ali, S., Andrade-Piedra, J., Bao, S., et al. 2016. Seed degeneration in potato: the need for an integrated seed health strategy to mitigate the problem in developing countries. *Plant Pathology* 65(1):3-16.
- Tibbitts, T., Cao, W., and Wheeler, R. 1994. Growth of potatoes for CELSS. NASA Contractor Report 177646. Ames Research Center, Moffett Field, California, USA.
- Tierno, R., Carrasco, A., Ritter, E., and de Galarreta, J.I.R. 2014. Differential growth response and minituber production of three potato cultivars under aeroponics and greenhouse bed culture. *American Journal of Potato Research* 91(4):346-353.
- USDA. 2015. The PLANTS Database (<http://plants.usda.gov>, 1 May 2018). National Plant Data Team, Greensboro, North Carolina, USA.
- Vintal, H., Ben-Noon, E., Shlevin, E., Yermiyahu, U., Shtienberg, D., et al. 1999. Influence of rate of soil fertilization on *Alternaria* leaf blight (*Alternaria dauci*) in carrots. *Phytoparasitica* 27(3):193.
- Vyvyan, M.C., and Travell, G.F. 1953. A method of growing trees with their roots in a nutrient mist. Annual Report. p. 95-98. East Malling Research Station, East Malling, Kent, UK.
- Wang, Q., and Zhang, W. 2004. China's potato industry and potential impacts on the global market. *American Journal of Potato Research* 81(2):101-109.
- Wang, Q., and Zhang, W. 2010. An economic analysis of potato demand in China. *American Journal of Potato Research* 87(3):245-252.
- Waters, G.C., Olabi, A., Hunter, J.B., Dixon, M.A., and Lasseur, C. 2002. Bioregenerative food system cost based on optimized menus for advanced life support. *Life Support and Biosphere Science* 8(3-4):199-210.
- Went, F.W. 1957. The experimental control of plant growth. The experimental control of plant growth. Ronald Press, New York, USA.
- Wheeler, R.M., Stutte, G.W., Subbarao, G., and Yorio, N.C. 2001. Plant growth and human life support for space travel. *Handbook of Plant and Crop Physiology* 2:925-941.
- Wheeler, R.M., and Tibbitts, T.W. 1986. Growth and tuberization of potato (*Solanum tuberosum* L.) under continuous light. *Plant Physiology* 80(3):801-804.
- Wheeler, R.M., and Tibbitts, T.W. 1989. Utilization of potatoes for life support systems in space. IV. Effect of CO<sub>2</sub> enrichment. *American Potato Journal* 66(1):25-34.
- Zheng, S.-L., Wang, L.-J., Wan, N.-X., Zhong, L., Zhou, S.-M., et al. 2016. Response of potato tuber number and spatial distribution to plant density in different growing seasons in Southwest China. *Frontiers in Plant Science* 7:365.