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Protected cultivation in tropical tuber crops – A review

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Abstract

Protected cultivation is being promoted as an innovative solution to address challenges of increasing demand in food production to commensurate with the population increase, limited cultivable area and unfavorable growing conditions. The advantages of protected cultivation include efficient use of water and nutrients, higher yield per unit area, year-round and offseason production, reduction in pests and diseases, and assured produce quality. Specific to tuber crops, protected cultivation offers benefits such as *in vivo* rapid multiplication of virus-indexed planting material, increased production and productivity and business opportunities in production systems. Different techniques have been explored for protected cultivation of specific tuber crops. Hydroponics and aeroponics have been used for cassava and yams resulting in improved survival rates, multiplication rates and root/tuber development. Sandponics systems have been developed for sweet potato pre-basic seed production, leading to higher vine multiplication rates and storage root yields. Hydroponics studies also revealed the pivotal role of potassium fertilizers in tuber crops, especially sweet potato. Optimum potassium doses can help to promote storage root development while maintaining a balanced shoot growth. It also helps to improve the quality characteristics of sweet potatoes, and tolerate stress including environmental stresses such as drought, salinity and diseases. The prospects of protected cultivation in tuber crops include standardization of production technology, including biofortified varieties and the integration of different methods of seed production to meet the required quality of planting materials. Ongoing research and development efforts are expected to drive innovation in hydroponics and aeroponics, leading to increased efficiency and productivity in tuber crops.

Keywords : Root and tuber crops, Protected cultivation, Hydroponics, Aeroponics, Soilless cultivation, Seed multiplication

Introduction

The earth's population has increased rapidly and is likely to reach 9.1 billion by the year 2050. The major challenge in the coming decades is to feed and provide shelter to this ever-increasing population and conserve the available natural resources and environment. The challenge to agriculture in the next few decades is to achieve maximum production of food without further irreversible depletion or destruction of our natural resources. The population increase is significantly higher in developing countries. Urbanization will continue at an accelerated pace, and about 70 percent of the world's population will be urban, compared to 49 percent today. Hence, to address challenges like growing demand for food, limited cultivable area, unfavourable growing conditions due to biotic and abiotic stresses by climate change, various innovative agriculture production technologies are being

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promoted globally. This allows efficient utilization of land and water resources and makes production possible under adverse climatic conditions. Protected cultivation such as soil-less/hydroponics and vertical farming has been suggested as an important solution (Pradhan and Deo, 2019; NAAS, 2019). It involves growing crops in environmental conditions where one or more of the production factors are under control. It can be nutrition, water supply, temperature, humidity, sunlight, or CO_2. This encompasses growing plants in simple shade nets and insect proof nets to growing plants in fully climate-controlled growth facilities by smart farming, vertical farming and urban farming. The high tech, fully automated facilities with multilayered cropping and soilless production systems will help humankind in the future space missions to meet the clean food and oxygen demands by growing the crops with minimal inputs under less available growth space (Hill et al., 1989).

Merits and demerits of protected cultivation system

It is customary to unravel the major advantages and disadvantages of protected cultivation system (NAAS, 2019; Singh, 2021; Sardare, 2013; Pradhan and Deo, 2019; Savvas and Gruda, 2018, Gautam et al., 2021, Salam et al., 2014). These are described below.

General advantages of protected cultivation system

- Efficient use of Water: more than 90% water saving is possible.
- Efficient use of nutrients: the quantity required is less, there is no leaching loss or fixation in soil.
- Higher yield per unit area as compared to conventional cultivation. For example, tomato yields 80-100 t ha^{-1} in conventional open field soil cultivation whereas in protected system, it yields up to 350-400 t from the same area.
- Year round and offseason production is possible to capitalize on lean season markets.
- Production is possible in unfavourable soil and climates like saline and waterlogged conditions and in deserts
- Reduction in pests and diseases as compared to soil based cultivation.
- Assured to produce quality in terms of safety, consistency and freshness
- The method is useful for speed breeding (shortened crop cycle) and phenomic studies.
- Possible solution to reduce food miles through urban and peri-urban farming.

Advantages specific to tuber crops

- This technique is useful for virus indexed *in vitro* seed material multiplication for clean seed (pathogen free) production through manipulation of microclimate in insect proof greenhouses.
- Creation of successful nurseries is possible from seeds or by vegetative propagation.
- Rapid multiplication of planting material is possible under inclement climatic conditions.
- Greenhouse facility could be used round the year to meet the planting material demands.
- High value and high quality planting materials could be grown for domestic as well as export markets.
- Income from small land holdings could be increased several-fold (business opportunities in production system).
- Increased production and productivity of ware tuber as well as seed tuber.

The major drawbacks of protected cultivation systems include high initial investment, greater skill and supervision, great loss or complete failure in case of improper management, non-availability of trained manpower and local non availability of inputs.

While the protected cultivation has been developed for many crops especially horticultural crops, its exploitation in tuber crops is at nascent stage. The use of aeroponics (a system where roots are grown continuously or discontinuously in an environment saturated with a mist or aerosol of nutrient solution) in the successful production of several horticultural and ornamental crops is reported by Biddinger et al., (1998). Encouraging results of growing tuber crops under protected conditions have been reported and this paper is an effort to review such studies.

Cassava

Cassava is one of the important tropical tuber crops worldwide and shortage of planting materials is the main limiting factor for its spread (Wang et al., 2014). Though tissue culture protocol is available, acclimatization of plantlets is a challenge. Major losses of *in vitro* plants occur during direct transplanting from test tubes to the *ex-vitro* condition. Direct transplanting is very sensitive for cassava. Simple hydroponic system can accelerate the plant acclimation, multiplication and can increase the survival rate of *in vitro* raised cassava plants. Castaneda-Mendez et al*.,* (2017) developed a hydroponic system for *in vitro* raised cassava plantlets. Six-week-old *in vitro* raised cassava plantlets were transferred to greenhouse condition for 6 days to facilitate their adaptation. Adapted plants were then treated with fungicide and transferred to sterilized sponge and allowed to float in hydroponic solution with an average temperature of 30˚C and relative humidity of 45% in natural light condition. This system considerably increased the survival percentage of *in vitro* and/or transgenic lines and reduces the time requirement for multiplication by hydroponic acclimation. Selvaraj et al., (2019) reported a low-cost aeroponic mist system that allows for real-time monitoring of storage root development in cassava. Accordingly, induction of the initial root thickening and bulking of cassava was achieved in aeroponic system. Aeroponics/hydroponics system can be useful in unraveling the hormonal regulation of tuberous root formation, root thickening etc. Auxin plays a crucial role in the formation of storage roots in plants, including cassava. It promotes the initiation of storage root development, stimulates root thickening and bulking, regulates root architecture and interacts with other hormones to ensure proper storage root formation. Tokunaga et al., (2020) reported an efficient method of propagating cassava plants using aeroponic culture. Accordingly , the aeroponic system has clear advantages over other propagation methods, such as tissue culture and soil propagation, as it allows for the multiplication of cassava plants three times every six weeks. It is low cost, uses readily available equipment, and has a low risk of bacterial contamination.

The performance of cassava plantlets using different substrates for stem-cutting multiplication under Semi-Autotrophic Hydroponics (SAH) technology was reported by Mamy et al., (2023). Cuttings were placed in 500 ml substrate-filled boxes and watered weekly with a 100 ml Miracle Gro solution. SAH was aimed at addressing the challenges faced by the cassava seed system, such as limited seed stock, slow propagation rate, lengthy growth period and lack of phytosanitary guarantees. Accordingly, KlasmannTS3 substrate consistently led to the highest survival rates and superior performance in terms of plant height, leaf numbers, and internodes development. Number of internodes and cuttings varied among genotypes and substrates, with KlasmannTS3 consistently resulting in the highest values. KlasmannTS3 substrate demonstrated the highest survival rate and cutting number, making it the superior substrate.

Yams

Traditional methods of yam propagation using tubers have a low multiplication rate of 1:10 compared to 1:100 in cereals (Mbanaso et al., 2011). Hence, efforts were made to accelerate the seed multiplication in yams. Awologbi and Hamadina (2015) studied the effect of fluridone, an ABA inhibitor, on the sprouting of yam tubers in a hydroponics system. Newly produced seed tubers had adventitious roots and no new shoots, while fluridone treatments resulted in renewed vegetative growth with new shoots developing from the small corm-like structure and/or from the surface of the tuber. Fluridone treatments led to earlier sprouting of newly produced tubers compared to the control group in hydroponic system**.**

The use of aeroponics in yam production can help address the challenges of low multiplication rates, high seed costs, and the build-up of diseases and pests associated with traditional propagation methods. Maroya et al., (2014) tested fresh vine cuttings of five yam genotypes of two species (*Dioscorea rotundata* and *D. alata*) in an aeroponics system. Vines cuttings from five month old plants established very good rooting system (95%) within 14 days with an average temperature of 20.3 to 33.8°C. Vines of both *D. rotundata* and *D. alata* rooted with varying rooting percentages among genotypes. Mini tubers harvested at 4 and 6 months after planting weighed 0.2 to 2.7 g and 110 g, respectively. This method has the potential to increase the propagation ratio, produce seed tubers of larger sizes and ensure high seed quality. Acheampong et al., (2020) reported successful propagation of both the genotypes of yams, viz., *D. rotundata* and *D. alata* in aeroponics using both pre-rooted and fresh vine cuttings.

The economic analysis determining the feasibility and viability of using aeroponics in seed yam production indicated that the variable cost constituted about 93% of the total production cost per season, while the fixed cost constituted 7% and BC ratio was 1.4 (Acheampong et al., 2020). Accordingly, a combination of tissue culture and aeroponics system is considered a way to ensure clean and adequate supply of seed yam for enhanced yam production.

Aighewi et al., (2015) described various methods of seed yam production including minisett technique, tissue and organ culture, aeroponics and temporary immersion bioreactor system which involves immersing yam plants in a liquid nutrient medium in a timed manner to address the challenges of quantity and quality of seed tubers. Accordingly, tissue and organ culture techniques offer rapid multiplication of disease-free propagules, but they are limited by high costs, the need for skilled personnel and specialized equipment. Aeroponics and temporary immersion bioreactor methods have shown potential for improving seed yam propagation rates and quality of seed tubers. Hence, an integrated multiplication scheme that combines two or more methods of seed yam production should be adopted.

Sweet potato

Sweet potato [*Ipomoea batatas* (L.) Lam.] is among eight crops selected by NASA for its Controlled Ecological Life Support Systems (CELSS) program (Mortley et al., 1991). Storage root yield plant^{-1} of sweet potato under hydroponics cultivation increased with CO_2 up to 750 μmol mol^{-1} (Mortley et al., 1996). In a flowing system with recirculation, designed at Tuskegee University using NFT (nutrient film technique), storage yield as high as 1790 g were produced with edible growth rate of 66 gm^{-2} day^{-1} and a harvest index as high as 89% under greenhouse condition (Hill et al., 1989).

Lack of Access to quality sweet potato planting material limits the utilization of improved and new varieties. Makokha et al., (2019) described the sandponics system with screen house used for sweet potato pre-basic seed production. Fertigation of vines in the sandponics system is done using drippers connected to an elevated tank containing nutrient solution. The optimum temperature range for sweet potato vine growth in the sandponics system was 22°C to 30°C. Harvesting of vines in the sandponics system could start 6 weeks after planting. Sweet potato pre-basic seed production using the sandponics system offers a more sustainable and cost-effective method compared to the conventional soil substrate method. It gave higher vine multiplication rate (VMR) of 27.6±1.2 and production efficiency compared to the conventional soil substrate method. Sweet potato pre-basic seed multiplied in the sandponics system has been found to have higher storage root yields compared to the conventional soil substrate method. Hence, it forms a dependable supply system of high-quality planting materials for sweet potato production.

Wanjala et al., (2020) explored the use of sandponics technology to improve the rapid multiplication of sweet potato pre-basic seed in East Africa. The sandponics system provides optimal growing conditions for sweet potato vines due to precise control of the nutrient solution. Vine multiplication rate (VMR) was 33% higher in the sandponics system compared to the conventional soil method of multiplying sweet potato vines. Among the cultivars studied, Irene had the highest VMR of 65.2 in sand and 45.5 in soil showing the genotypic difference in VMR. Further research is needed to explore alternative, locally available sources of fertilizers to reduce the cost of production in the sandponics method and increase its cost-effectiveness.

The soil environment, including nutrient availability and moisture levels, also affects tuberous root development. Sakamoto and Suzuki (2018) developed a new hydroponic cultivation system in which tuberous roots were grown in solid media in the pots whereas fibrous roots were grown in the nutrient solution. When plants were grown in small-sized pots (1.6 L), the fresh weight of the top and tuberous roots decreased compared to plants grown in larger pots (3.0 L and 4.5 L). Studies have shown that humidity is an important factor for the development of tuberous roots in sweet potato. Further, root zone temperature also influenced tuberous root enlargement.

Sakamoto and Suzuki (2020) reported that nutrient solution concentration, specifically the electrical conductivity (EC), affects sweet potato growth characteristics. The optimal EC range for sweet potato plants in hydroponics is generally between 1.5 to 2.5 dS m^{-1}. High nutrient solution concentrations can reduce growth and photosynthetic parameters, while sweet potato plants can tolerate EC up to 3.6 dS m^{-1}. Nutritional requirements vary with the developmental stage. The rate of N application influences the development of lateral roots at the early growth stage. However, at higher N doses, the storage root biomass decreases while the shoot biomass increases. Administering an adequate quantity of potassium (K) fertilizer can also increase the ratio of storage root yield relative to the total yield. Finding the right balance in N fertilizer application is crucial for achieving the desired biomass partitioning and optimizing crop productivity in sweet potatoes.

Providing the right amount and quality of light is essential for maximizing productivity and ensuring high-quality harvests. Lighting conditions, including light intensity and light quality, play a crucial role in determining the overall productivity and quality of sweet potato plants. Sweet potato leaves grown under supplemental LED lighting under tropical greenhouse condition had higher leaf fresh weight and dry weight, higher concentrations of chlorophyll and carotenoids, higher photosynthetic CO_2 assimilation rate and stomatal conductance compared to leaves grown under natural sunlight (He and Qin, 2020).

Leaves grown under supplemental LED lighting had lower midday Fv/Fm ratio, higher electron transport rate and photochemical quenching, but lower non-photochemical quenching compared to leaves grown under natural sunlight. Several studies highlighted the importance of optimizing light period and irradiance in hydroponic systems to maximize the yield and biomass production of sweet potatoes. Mortley et al., (2009) investigated the influence of daily light period and irradiance on the growth, yield and elemental composition of hydroponically grown sweet potatoes. Longer daily light periods and lower irradiance resulted in greater storage root yield and biomass production. The number of leaves was higher in plants grown under shorter light periods and higher irradiance. Leaves of plants grown under longer light periods and lower irradiance had lower concentrations of various elements. There were no significant differences in leaf elemental concentration between the two cultivars evaluated.

Taro

Use of hydroponic system for taro plants was reported by Nhut et al., (2004). They acclimatized *in vitro* plantlets with well developed roots in hydroponic system in the greenhouse at 25+2°C, 85-90% relative humidity and under natural light. Cupric sulphate pentahydrate ($CuSO_4.5H_2O$) was used to control golden apple snail in taro plants under hydroponic cultivation (Hill and Miyasaka, 2000). Two hydroponic, greenhouse studies revealed the effects of Cu^{2+} levels on taro growth, the Cu^{2+} toxicity threshold, and useful diagnostic indicators of Cu toxicity. The Cu^{2+} toxicity threshold for young taro plants was found to be 1.2 M. Further, taro plants grown in the higher Cu^{2+} levels also exhibited a pattern of tip necrosis in older leaves, covering up to one-quarter of the most severely affected leaves. Excessive root zone Cu^{2+} resulted in a shift in root morphology to thicker, shorter roots. Ansari et al., (2015) reported the feasibility and benefits of growing taro in hydroponics using vermiwash as a nutrient-rich alternative to chemical fertilizers. Hydroponic system that is appropriate for taro cultivation could be a nutrient film technique (NFT) system, deep water culture (DWC) system, or any other suitable hydroponic system. Taro generally prefers a slightly acidic pH range of 5.5-6.5, temperature between 25-30^{0}C and a humidity level around 70-80%.

An effective procedure for the acclimatization of *in vitro* produced plantlets of taro using hydroponic system was described by Nhut et al., (2004). Comparisons between *in vitro* taro plantlets acclimatized in soil and in a hydroponic system indicated that the plantlets in the hydroponic system showed higher survival rates, plant height, number of leaves, and number of micro tubers compared to those in soil culture. Micro tubers were formed after culturing the taro plantlets in the hydroponic system for 15 or 30 days. The taro plantlets acclimated in the hydroponic system had superior performance when transferred to the field compared to those from the soil system indicating that the hydroponic system prepared the plantlets for successful establishment and growth in the field, potentially leading to higher yields. Tuwo and Tambaru (2021) compared the acclimatization media for tissue culture plants of taro. The plantlets were planted in plastic cups with the different substrate mixture namely soil: manure: rice husks (1:1:1); soil: manure: cocopeat (1:1:2); rice husk: sand (1:1) and nutrient film technique (NFT) hydroponics system. Accordingly, the optimal acclimatization medium for taro plantlets were a mixture of soil: manure: rice husks giving the maximum survival of 62%, high mean plant height (13.3cm) and average number of leaves (4.6).

Coleus sp.

In the case of Coleus (*Plectranthus barbatus* Andr.), among the different media and nutrients evaluated, plants grown under coco peat media with 80% of the recommended dose of fertilizer for soil (864, 768 and 960 mg plant^{-1} of N, P and K, respectively) recorded significantly higher root yield (17.10 t ha^{-1}) and quality (0.98% forskolin). Benefit-cost ratio was also recorded maximum (4.25) in the same treatment. Vermiculite media promoted root growth compared to shoot growth (Sharma and Vasundhara, 2015). Hence, there is scope for growing vegetable type coleus/Chinese potato (*Plectranthus rotundifolius* (Poir.) Spreng) on soilless culture and it will be the answer to overcome problem of root knot nematode, root rot and wilt complex along with increasing yield and quality of tuberous roots.

Future prospects

Emerging techniques of hydroponics and aeroponics systems of cultivation under protected conditions could become the natural choice for seed material multiplication in tropical tuber crops. In addition, standardization of production technology for edible roots and tubers under protected cultivation can help adopting such crops in urban and peri-urban areas, in addition to the existing village areas. By adopting such methods, tuber crops varieties could be produced in large quantities round the year. Bio-fortified varieties like orange fleshed sweet potato and anthocyanin rich sweet potato, and greater yam varieties would help combat malnutrition and serve industries for processing and also act as a very effective natural colorant. Moreover, safety of produce assured due to limited or no use of plant protection chemicals under greenhouse systems of production. Hence, it is imperative to evaluate the suitability of tuber crops in protected farming with the aim of rapid multiplication of quality planting materials as well as increase in production, reduce crop duration and above all increased productivity. This may require standardization of substrate, nutrient dosing and environmental parameters for protected farming and in turn development of complete protocol for protected framing of tropical roots and tubers. Ongoing research and development efforts will continue to drive innovation in the hydroponics industry. This includes the development of new nutrient solutions, improved growing techniques, and the exploration of alternative growing mediums. These advancements will further enhance the efficiency and productivity of hydroponic systems. As consumers become more educated about the benefits of hydroponics, there will be increased acceptance and demand for hydroponically grown produce. This will create opportunities for hydroponic farmers to expand their market reach and establish stronger linkages with various stake holders especially with consumers.

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