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Development of an Industrial-size Aeroponic Rooting System and Plant Cutting Rooting Studies

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Abstract

Aeroponic agriculture is an innovative system that allows plants to grow and develop by by misting water directly onto the bare root zone. Thus, oxygen and water, which often limit root growth in traditional soil-based systems, can be provided at optimal levels in this system. Within the scope of the study, an industrial-sized aeroponic rooting unit was designed and manufactured. After drawings were made in the digital environment, the manufacturing process started. The unit consists of three vertical lines, each composed of three levels. Nine cabins were produced, each cabin measuring 2x0.4x1 m. The control unit is designed to independently control each cabin's humidity, temperature, lighting, and ventilation features. The study examined the potential of aeroponic agriculture, focusing primarily on the effects of the aeroponic system on the growth of plant roots and its performance on various plant species. Within the scope of the study, the rooting performances of black mulberry (*Morus nigra*) and Judas tree (*Cercis siliquastrum*) cuttings, which are very difficult to root with traditional methods, were examined in perlite and aeroponic environments. The effect of cutting time, growth regulator doses, and various parameters on root formation and development during the rooting process were examined. In black mulberry hardwood cuttings, 6000 ppm IBA application in the aeroponic system resulted in the highest rooting rate (85.19%) and callus formation rate (96.30%). The rooting rate of black mulberry wood cuttings in perlite medium with 6000 ppm IBA application was 59.26%. Application of 4000 ppm IBA on black mulberry green cuttings in the aeroponic system reached the highest callus formation rate (92.59%) and rooting rate (81.48%). These values show a significant increase compared to the control group. At the same time, the highest rooting rate (74.08%) in perlite medium was again obtained with 4000 ppm IBA application. Application of 6000 ppm IBA to Judas tree green cuttings in the aeroponic system reached the highest rooting rate (29.63%) and callus formation rate (25.92%). It has been observed that the aeroponic system is more successful in terms of rooting rates and number of roots compared to perlite media.
Keywords: Aeroponic, Sustainable Agriculture, Cutting Rooting, Sapling Production, Water Saving, *Black Mulberry*, *Morus nigra*, Judas Tree*, Cercis siliquastrum*

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INTRODUCTION

Today's agriculture is adopting new technologies to respond to rapidly increasing and changing needs. The most important of these technologies are hydroponic and aeroponic systems, which are soilless plant growing methods. These methods allow plants to be grown without soil and differ from traditional agricultural practices by applying water and nutrients directly to plant roots. Hydroponic and aeroponic systems are considered high technology in the agricultural sector (Lakhiar et al. 2018).

An aeroponic system is a growing technique in which plants are suspended in air. Water and nutrient solution is applied to plant roots and rooting areas in mist, allowing plant development to be accelerated and roots to be formed healthily (Keeratiurai, 2013; Benke, 2017; Hinds, 2022).

Studies show that aeroponic methods offer distinct advantages in plant-growing processes. In particular, (Sharma et al., 2018) indicates that the rooting success of plants propagated by cuttings in an aeroponic environment is significantly higher compared to the soil environment. The advantages of aeroponic systems, such as water use efficiency, disease-free plant production, and access to the root system, are also emphasized (AlShrouf, 2017).

Aeroponic farming offers distinct advantages compared to other hydroponic systems, and available data suggest that it has the potential to initiate a new revolution in agricultural production. Tokunaga et al. (2020) found that aeroponic systems are very effective in producing plants free from soil-borne diseases and are more advantageous than other methods regarding speed and efficiency in the rooting process. These advantages were also supported by Rostami & Mohavedi (2016) who showed that aeroponic systems gave successful results in parameters such as root length and root volume.

This method allows plants to grow faster. It provides higher yields than traditional agriculture and other hydroponic methods, thanks to the contact of the roots with air and the rich content of the nutrient solution. It also offers a more efficient approach to water and nutrient use. Aeroponics also makes it possible to grow plants in areas experiencing soil scarcity or pollution. Indoor cultivation requires minimum use of pesticides, reducing the risk of harmful organisms and diseases. With these features, aeroponic agriculture is a potentially critical future modern agriculture method (Souret et al., 2000).

In addition, aeroponic systems provide adequate protection against soil-borne diseases and pests and advantages such as water use efficiency and reusability of the nutrient solution. Thanks to this system, obtaining high efficiency from unit area, rapid growth of plants, and increasing their reproduction potential will be essential steps in sapling and agricultural production (Ritter, 2001; Hayden, 2002; Cai, 2023).

Thanks to the aeroponic system, spraying water and rooting stimulants to the bottom of the cuttings offers the advantages of soilless agriculture, reducing the costs and labor requirements arising from traditional substrate use.

Many studies on aeroponic systems have been conducted around the world. However, most of these studies were conducted under laboratory conditions and at trial sizes. This study reveals the effectiveness and potential of aeroponic rooting systems in agricultural production. The data presented in the literature emphasize that aeroponic methods are an essential step in sustainable agriculture and indicate that these systems may become widespread in future agricultural practices. In our study, a system for mass production at an industrial scale, which can be used by manufacturers and supported by renewable energy sources (Solar energy), was designed, and field trials were carried out. The rooting system produced is a commercial product to be delivered to end users.

MATERIAL METHOD

The study was conducted in the plastic greenhouse at Tokat Gaziosmanpaşa University Agricultural Research and Application Center. An industrial-sized Aeroponic rooting unit was installed in the greenhouse, and trials were carried out in this unit (Figure 1). The rooting unit was designed and manufactured by the team. Statistical analyses were performed using SAS (9.0) package program.

Figure 1. The rooting unit was designed and manufactured by the team

There is no need for rooting media such as perlite, peat, or soil in the unit designed for propagation by cuttings. The cuttings are kept suspended in the air, and water and rooting stimulants are applied to the bottom of the cuttings as a spray.

Drawing the Rooting System in a Digital Environment

The rooting unit, which was initially designed in advance, was then digitally created as a 3D image in the SOLID program. All system parts were drawn to scale, with connection points, and digitally combined. Preparations for manufacturing were made by creating detailed drawings showing all the components and how they worked.

The system is designed as three floors and three lines. It consists of 3 cabins on each floor, each with a 2 m^2 reproduction area. This way, six cutting rooting areas are created on each floor, totaling 18 m^2. The depth of the crates is designed to be

40 cm, and the distance between floors is 50 cm. The design has been made so that the number of floors and cabins can be increased/decreased in case of need and demand. The rooting unit is designed to be completely disassembled.

Creation of mechanical parts

Main Skeleton Metal Part Manufacturing

The metal parts that will form the skeleton of the cabins are made of a 2 mm-thick steel profile with dimensions of 40x40 mm to be durable. In order to provide resistance against stretching, four vertical and four cross profiles were used. Six horizontal and 12-depth axis profiles were used to create the floors. The length of the vertical profiles is 3 meters, the size of the horizontal profiles is 2 meters, and the length of the deep profiles is 1 meter. The profiles used formed the main skeleton (Figure 2). The head parts of the metal profiles are fixed with “L” supports and screws.

Figure 2. Main Skeleton Metal Part Manufacturing

Rooting crates manufacturing

The crates where the lower parts of the cuttings will be located are produced from stainless galvanized panels with dimensions of 200 mm x 100 mm x 40 mm. Insulation is made with industrial silicone to ensure sealing at the junctions of the crates. The front parts of the crates are designed as opening lids. The compartment inside the cover crates allows control of the system when needed.

Irrigation/Humidification system

The areas where the cuttings will be rooted are moistened with misting nozzles installed inside the crates. The irrigation heads have an adjustable spray diameter of 0.30 mm (30 μ). As a result of the research, it was determined that metal irrigation heads wear and rust over time in aeroponic and similar systems. For this reason, plastic irrigation heads were preferred. Fogging nozzles placed in the crates' upper area moisten the cuttings' upper parts as needed. In the irrigation system, all crates can operate independently of each other at different time intervals. High-pressure-resistant black plastic pipes with a diameter of 8 mm were used in the rooting cabinet to ensure long life (Figure 3).

Figure 3. Irrigation/Humidification system

Heating system placement and temperature control

In the working principle of rooting systems in plants, the lower parts of the cuttings must be kept warm, and the upper parts must be kept cool. In line with this principle, the lower parts of the crates are set between 20-22 C with heating pads, and the heaters keep the cabin within these temperature ranges. Heating pads are placed between the sheet metal crates and the insulation material. In this way, the heating pads are both protected and enabled to transmit heat directly to the interior of the crates (Figure 4).

Figure 4. Heating system placement and temperature control

The surroundings of the rooting cabins were covered with 6 mm polyethylene insulation material to minimize heat loss and save energy. A 5 mm composite coating was applied on top of it. The lower parts of the crates are covered with unique adhesive coating material. Heating pads align with the data of the cabin temperature sensors connected to the automation system.

Support Elements

The cabins are covered with a metal support system so the cuttings can stand on their hangers. The metal protectors manufactured on the cabin are made of 20 mm profile metal. Profile holders have a wheeled system and are designed to be mobile. Styrofoam vials were used to hold the cuttings. Each vial has 210 cells, and the total production capacity is 15,000 cuttings.

Side Windows: The top and side parts of the rooting crates are covered with an openable 3 mm transparent plexiglass material. One 500-liter and two 200-liter plastic water tanks were used for fogging. Circulation fans have been placed to ensure air circulation within the rooting box and between the cabinets. The fans operate depending on the PLC system according to humidity measurement data and temperature sensors. The outer surface of the system is completely covered with white composite material, making it a durable and easily processable material. In addition to its visuality and functionality, it also provides significant heat insulation.

Design and Manufacturing of Control System

The PLC control unit can control processes such as heating, humidification, and application of plant nutrients. It can manage all cabins simultaneously or independently of each other. The PLC control unit is designed according to need and has an expandable structure (Figure 5). Thanks to this feature, it can gain the ability to control larger-scale systems.

Figure 5. Design and Manufacturing of Control System

Rooting of Black Mulberry and Judas Tree Wood/Green Cuttings

After the rooting unit was operational, the wood cuttings were placed into the system. The "black mulberry" and "judas tree" cuttings used in the study were obtained from Tokat Gaziosmanpaşa University Research and Application Center. Cuttings taken from suitable trees were cut into approximately 20 cm lengths according to their node condition and prepared for planting. The equipment used in cuttings has been disinfected with alcohol against the risk of disease transmission. Before the cuttings were planted in the system, they were washed to remove foreign substances. The cuttings were not stored anywhere and were placed in the system on the day of cutting.

The trials were planned with three different repetitions, and three different doses of IBA (indole-3-butyric acid) (2000 ppm, 4000 ppm, 6000 ppm) were applied to encourage rooting.

This rooting process aims to evaluate the effectiveness of the aeroponic rooting unit developed to root wood and green cuttings. In order to compare the experiments installed in the aeroponic system, the same experiment was also conducted in the perlite rooting medium (Figure 6).

Figure 6. Rooting of Black Mulberry and Judas Tree Wood/Green Cuttings

RESULTS AND DISCUSSION

When the rooting performance of black mulberry wood cuttings is examined, Positive effects of high-dose IBA applications on callus formation (Figure 7) and rooting (Figure 8) rate were observed, especially in the aeroponic system. Cuttings that have begun to form callus and develop roots. Developmental processes in an aeroponic environment are shown. Applying 6000 ppm IBA in the aeroponic system reached the highest rooting rate (85.19%) and callus formation rate (96.30%). Similarly, the rooting rate was 59.26% in perlite medium with 6000 ppm IBA application. When the root quality parameters were examined, it was seen that the cuttings in the aeroponic system differed significantly from those in the perlite medium in terms of root length, root diameter, and number of roots (Table 1). While the average root length of the cuttings obtained with the application of 6000 ppm IBA in the aeroponic system was 7.45 cm, the highest value in the perlite medium was determined as 3.50 cm.

Figure 7. IBA applications on callus formation

Figure 8. Rooting performance

Table 1. Effect of different rooting systems on rooting parameters of black mulberry wood cuttings

Medium	IBA (ppm)	Decay Rate (%)	Callus Rate (%)	Rooting Rate (%)	Root Length (cm)	Root Diameter (cm)	Number of Roots (Piece)
Perlite	**Control**	0	7.41 c	18.52 b	3.43b	0.96	4.40
	2000	0	44.44 a	48.15 ab	4.66ab	1.55	7.60
	4000	0	25.93 b	55.56 a	4.76ab	1.32	7.59
	6000	0	22.22 b	59.26 a	5.74a	1.23	6.47
Aeroponic	**Control**	0	22.22 c	14.81 c	2.63c	1.63	5.50 b
	2000	0	51.85 b	40.73 b	3.68bc	2.22	8.67 a
	4000	0	88.89 a	77.78 a	5.44ab	1.71	8.28 ab
	6000	0	96.30 a	85.19 a	7.45a	2.05	8.37 ab

*There is a difference between growth dose applications indicated by different lowercase letters (P<0.05).

When the rooting performance of black mulberry green cuttings was examined, the effects of different growth regulator doses used in the aeroponic system on the decay rate, callus formation, and rooting rate were considered (Table 2). For example, 4000 ppm IBA application in the aeroponic system resulted in the highest callus formation rate (92.59%) and reached the rooting rate (81.48%). These values show a significant increase compared to the control group. At the same time, the highest rooting rate (74.08%) in perlite medium was obtained with 4000 ppm IBA application. When examining rooting performance, root length, root diameter, and number of roots of cuttings in the aeroponic system differed significantly compared to the control groups. For example, while the average root length of the cuttings obtained by applying 4000 ppm IBA in the aeroponic system was 2.27 cm, this value was determined as 0.06 cm in the cuttings in the control group.

Table 2. Effect of different rooting systems on rooting parameters of black mulberry green cuttings

Medium	IBA (ppm)	Decay Rate (%)	Callus Rate (%)	Rooting Rate (%)	Root Length (cm)	Root Diameter (cm)	Number of Roots (Piece)
Perlite	**Control**	7.41	77.78	48.15	1.62	0.29	1.52
	2000	0	77.78	55.56	2.54	0.47	1.26
	4000	14.81	85.19	74.08	3.45	0.76	6.78
	6000	18.52	81.48	66.67	3.50	0.68	4.63
Aeroponic	**Control**	0	7.41 c	7.41 c	0.06 b	0.11 b	0.11 b
	2000	3.70	70.37 b	62.97 b	1.90 a	0.46 a	1.22 b
	4000	3.70	92.59 a	81.48 a	2.27 a	0.60 a	4.58 a
	6000	0	74.08 b	66.67 b	1.29 ab	0.50 a	4.52 a

*There is a difference between growth dose applications indicated by different lowercase letters (P<0.05).

When the rooting performance of Judas tree green cuttings was examined, the effects of high-dose IBA applications in the aeroponic system on callus formation and rooting rates were evident. Applying 6000 ppm IBA in the aeroponic system reached the highest rooting rate (29.63%) and callus formation rate (25.92%). When the rooting parameters were examined, it was observed that the cuttings obtained in the aeroponic system showed a significant difference compared to those in perlite medium in terms of root length, root diameter, and number of roots. For example, while the average root length of the cuttings obtained by applying 6000 ppm IBA in the aeroponic system was 5.43 cm, the highest value in the perlite medium was 4.50 cm (Table 3).

Table 3. Effect of different rooting systems on rooting parameters of Judas tree green cuttings

Medium	IBA (ppm)	Decay Rate (%)	Callus Rate (%)	Rooting Rate (%)	Root Length (cm)	Root Diameter (cm)	Number of Roots (Piece)
Perlite	**Control**	22.22 a	7.41 b	3.70 b	0.70 c	0.33 b	0.50 b
	2000	18.52 a	7.41 b	3.70 b	4.50 a	0.80 a	1.00 ab
	4000	3.70 b	14.81 ab	7.41 ab	2.20 b	0.60 ab	0.63 b
	6000	14.81 ab	22.22 a	14.81 a	2.80 b	0.74 a	2.33 a
Aeroponic	**Control**	0.00 b	0.00 b	3.70 c	2.10 b	1.10	1.00 b
	2000	0.00 b	11.11 ab	11.11 bc	4.73 a	1.51	1.07 b
	4000	0.00 b	25.92 a	25.92 ab	2.76 b	0.94	4.30 a
	6000	3,70 a	25,92 a	29,63 a	5,43 a	1,47	5,13 a

*There is a difference between growth dose applications indicated by different lowercase letters (P<0.05).

The data shows that high-dose IBA applications, especially in the aeroponic system, positively affect cuttings' rooting performance and quality and significantly improve the rooting process (Figure 9). Enslaved cuttings that have completed their development in an aeroponic environment and are ready for planting in the training area.

Figure 9. Rooting performance

Note: It has been observed that the rooted plant cuttings removed from the aeroponic system need intense watering depending on the environmental conditions during the first week following pot planting to adapt to arid conditions.

Many research and academic studies emphasize the critical role that aeroponic agriculture can play in the agricultural sector today and in the future. Current literature shows that soilless farming methods are becoming increasingly important. In particular, it is stated that technologies such as aeroponic rooting can offer a solution-oriented approach to plant cultivation. In light of the research, it has been concluded that soilless farming techniques will be essential in the agricultural sector's future.

According to the United Nations FAO report, according to Kaur et al. (2023), there will be a tremendous demand for food worldwide, expected to increase by 70% by 2050. It has been stated that basic parameters such as decreasing resources, global population, and climate change have become challenging for traditional agriculture. He stated that modern farming practices, such as soilless farming techniques, will help farmers eliminate the above challenges in today's scenario.

Armi et al. (2023) stated in a study on lettuce that hydroponic and aeroponic systems have a significant impact due to the adaptation of components such as organic fertilizers and other factors affecting the availability of essential nutrients. Both systems affected growth parameters such as plant height, number of leaves, fresh plant weight, dry plant weight, and shoot-root ratio. They also revealed that it increased the yield and quality parameters of lettuce.

In a study by Kratsch et al. (2006), Aeroponics was defined as a suitable alternative to other soilless culture systems to protect plants with a controlled root zone atmosphere. In the study, extra-fine mist nozzles were controlled by a programmable timer, which periodically sprayed the roots with nutrient solution. During on the effects of O_2 on the formation of root nodules, 100% survival of plants and abundant nodulation appeared after four weeks. As a result of the research, the aeroponic system is easy to construct with inexpensive materials, has many applications for rhizosphere biology, and is unique among previously used systems.

In their study, Baciu et al. (2023), aimed to evaluate the applicability of vertical farming techniques to mulberry cultivation in a controlled environment and their prospects for a more sustainable and safer agricultural practice. As a result of the study, it was stated that the aeroponic system could be adapted to a broader collection of functional plants, especially mulberry.

In 2004, Ed Harwood, the founder of "AeroFarms," developed an aeroponic system for growing lettuce in microfiber material, and thanks to his patented aeroponic technology, AeroFarms established the world's largest indoor vertical farm in its facility in New Jersey. With this technology, the farm can produce and sell up to two million pounds of leafy greens annually without pesticides (Anonymous, 2023).

Aeroponics is a total system that allows plants to grow and develop. It is an aerial water culture providing nutrients directly to the bare root system in water mist. Thus, oxygen and water, often a limiting growth factor in traditional soil and aquatic environment systems, are provided at sufficient levels. It also provides economic benefits in using fertilizer and water due to the reuse of the nutrient solution. Facilities, seasonal crop type, growth order, etc., can be operated continuously without attention (except for cleaning or plant changing). Additionally, the system saves space due to density and additional size. It has been stated that aeroponics will adapt very well to industrialized agriculture, although it allows maximum control of the growth process (Nir, 1982).

Many advantages of the aeroponic agricultural system have been revealed, mainly because it is a cheap and accessible technology, fast, year-round use, and high efficiency per unit area thanks to the layered system have been emphasized by researchers (Mateus-Rodriguez et al. 2013; Gurley, 2020). Researchers compared aeroponic technology's technical and economic aspects with other mini-tuber production systems developed in Latin America (conventional, semi-hydroponic, and fiber-cement tile technology). Research methodologies: 3-year recording of cash flows and aeroponic production records, economic and technical studies, and in-depth research with technology executivesThe results show that the aeroponic method, supported by the International Potato Center (CIP), has several advantages, including high multiplication rates (up to 1:45), high production efficiency per area (> 900 mini tubers per m^2), and savings on water and chemicals. The most significant disadvantage of the aeroponic technique is the possibility of irreversible damage or complete loss, as there is no substrate available to ensure the survival of the plants in the event of a technical outage or power outage (Li et al. 2018). For this purpose, providing a generator or a second alternative energy source to the systems will provide an essential solution to the risks.

In order to reveal the effectiveness of the system established for aeroponic rooting purposes, the effects of different rooting systems (perlite medium and aeroponic system), different growth regulator doses (different concentrations of IBA), and cutting periods on the rooting performance of black mulberry, Judas tree green and wood cuttings were investigated.

Criteria evaluating rooting performance include decay rate, callus rate, rooting rate, root length, root diameter, and number of roots. In the aeroponic system, higher rooting rates were observed in black mulberry and Judas tree wood cuttings, especially at high IBA doses (6000 ppm). Significant improvements were observed in this system regarding root quality, and longer, thicker, and more roots were obtained, especially in the aeroponic environment.

In the 1930s, auxins were discovered as chemicals that regulated plant growth and demonstrated their ability to promote adventitious rooting in the stem. The years have provided information on the absorption and translocation of auxin in cuttings and the effects of auxin timing. Basal rapid dipping, powder application, and dilute soaking methods were the most frequently used methods for application. A wide variety of other methods of auxin application have been reported, and they continue to this day. It has been stated that there are opportunities to develop further auxin application techniques that can improve plant quality (Blythe et al. 2007).

Callus formation has been noted as an essential step in the cutting process. It has been observed that high IBA doses increase callus formation, especially in the aeroponic system, and indirectly support rooting. Similarly, studies indicate that high IBA doses positively affect callus formation in an aeroponic environment.

A study conducted by Regas et al. (2021) on hemp describes the standardization of an efficient clonal propagation technique of cannabis using aeroponic systems. Primary shoot cuttings were removed from two cannabis species, 'Cherry Wine' and 'Red Robin' (CBD 17-20% w/w), which served as 'mother plants.' An auxin precursor (indole-3-butyric acid) was applied to stimulate root development in the basal part of the cuttings before placement in the system. Cuttings were lightly misted with nutrient mist solution every three days to provide nutritional support as the solution contains essential macronutrients, including nitrogen, phosphorus, and potassium. The aeroponic system water tank maintained a pH range of 5.0-6.0 and a water temperature of 20-22 °C. The shoot tip cuttings were given light 24 hours a day for ten days until root development occurred, and then the rooted cuttings were planted for research purposes. The method described here provides a more effective means of asexual propagation of cannabis by easing potential time constraints from traditional methods.

The absence of rot in wood cuttings was thought to be related to low irrigation amounts. This can be interpreted as wood cuttings showing better rooting success in lower humidity environments. The perlite medium gave results that were different from those of the aeroponic system regarding rooting performance. The aeroponic system gave more successful results, especially in Judas tree green cuttings. It has been observed that high IBA doses generally increase rooting performance. However, this effect varied depending on the cutting type and rooting environment (Akakpo et al. 2014).

In his research, Sukhjit (2015) investigated the rooting of wood cuttings of Shan-i-Punjab Peach with Indole-3-butyric acid (IBA) using different treatments. The base of the cuttings was applied with 1000 ppm, 2000 ppm, 3000 ppm, 4000 ppm, and 5000 ppm IBA for 1-2 minutes and planted under field conditions. He stated that the cuttings treated with 3000 ppm IBA for 1-2 minutes achieved significant success in terms of seedling rooting criteria (sprouting percentage, survival percentage, average number of roots, length of the primary root, root circumference, root weight, number of rooting days). A study has shown that IBA increases rooting rate and improves root quality (Özdemir et al. 2014).

The literature has stated that the propagation of the Judas tree plant results in lower success rates than other plants. In their study, Yılmaz & Yıldız (2020) stated that indole butyric acid (C) on the rooting performance of green cuttings taken from (*Cercis siliquastrum*, *Magnolia soulangeana*, *Spiraea salicifolia, Chaenomeles japonica, Philadelphus coronarius saxifragaceae, Syringa vulgaris, Lagerstroemia indica, Alcea rosea*). The effect of the IBA application was examined. 8000 ppm IBA was applied to (Cercis siliquastrum) cuttings, and 2000 ppm IBA was applied to cuttings taken from other species. (Cercis siliquastrum) Cuttings showed a low rooting success (6% and 10%) in both controls (0 ppm) and 8000 ppm IBA applications.

Considering that high IBA doses in the aeroponic system significantly increase rooting performance and root quality, optimizing these factors during the cutting process is essential for plant breeding. Cutting time and propagation environment should also be considered, as different results can be produced depending on the plant species. These findings may contribute to improving plant propagation processes and identifying more effective strategies in plant breeding practices.

Studies also suggest that the decay rate is related to the moisture level. It has been stated that lower irrigation amounts can reduce decay in plant materials, mainly wood cuttings, and provide better rooting in these environments (Salisbury el al. 1992).

There are similar findings in the literature regarding the success rates of different plant species in the process of propagation by cuttings. For example, research supports the idea that the propagation of some plant species by cuttings is more complex and has low success rates (Hartman et al. 2011).

As a result of Lakhiar's (2018) article, in which he compared dozens of aeroponic studies conducted worldwide, He stated that the aeroponic system is the best plant-growing technology in many respects compared to different growing systems.

In general, it can be concluded that, apart from the potential advantages of aeroponic systems, the correct use of these systems should be optimized depending on the plant species, cutting time, and growth regulator doses. These findings may provide essential guidance in improving plant propagation processes and identifying more effective agricultural practices.

CONCLUSIONS

Aeroponic rooting units have great potential in plant propagation processes. Studies have shown that aeroponic systems offer many advantages over other propagation methods. In particular, essential advantages such as high rooting success despite low auxin concentrations, disease-free plant growth, and rapid root development reveal the potential of this method.

These studies show that aeroponic rooting systems could be an essential solution for the agricultural industry. The fact that the system increases water use efficiency and requires less space can be a great advantage, especially with limited resources.

This system will also provide an essential solution for the nursery sector, making it easier to propagate plants with low efficiency during the propagation stage with cuttings, and production will be achieved at low costs. In addition, it has been observed that the system used for producing fruit, vineyard, and ornamental plants will enable the production of saplings and rootstocks quickly and healthily.

Among the advantages of the aeroponic rooting system are that it is a growing structure free from soil-borne diseases and pests, has water savings of up to 98%, has fertilizer savings of up to 60%, and has an environmentally friendly production process. In addition, the system's year-round use will accelerate the propagation and production processes for many plants and increase productivity.

More research and development is required for this method to become widely used and accepted. In particular, it is essential to diversify the studies on different plant species and make these systems more widely available commercially. In addition, training and awareness-raising activities for farmers and agricultural experts are required to increase the use of this technology.

As a result, aeroponic rooting units have a significant change and development potential in the agricultural sector. Further research, development, and dissemination of this technology can increase efficiency in agricultural production and play an essential role in food security in the future. Developing comprehensive and technologically equipped systems integrated with artificial intelligence will enable the creation of an economically and environmentally sustainable agricultural production model.

Compliance with Ethical Standards

Peer Review

This article has been reviewed by independent experts in the field using a rigorous double-blind peer review process.

Conflict of Interest

The authors declare no conflicts of interest.

Author Contributions

HK: Visualization, Conceptualization, Methodology, Data collection, Data analysis, Supervision, Writing - original draft, Review, and editing. HP: Visualization, Production, Conceptualization, Methodology OS: Data collection, Data analysis, Supervision, Writing MMC: Data collection, Data analysis, Supervision, Writing GY: Data collection, Data analysis KY: Writing – original draft, Review and editing.

Ethics Committee Approval

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