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DOÇ. DR. SALİH BATAL

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e-mail: seruvenyayinevi@gmail.com

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İÇİNDEKİLER

Chapter 1

DRIP IRRIGATION IN RICE CULTIVATION: ENHANCING WATER EFFICIENCY AND CROP YIELD

Birol TAŞ[1]

1 Prof. Dr. ,Bursa Uludag University Agricultural Faculty, Field Crop Dept, ORCID: 0000-0003-4975-0278

1. Introduction to Drip Irrigation and Rice Cultivation

Efficient water management is very important, especially due to drought or water scarcity in a region. On the one hand, water use efficiency (WUE) and increased water productivity per unit area must be promoted (Nkya et al., 2015). On the other hand, low-cost, effective, and sustainable methods should be selected. The studies showed that drip hose or pipe irrigation systems can potentially improve water use efficiency in agro-systems, and they can be adapted and used in greenhouse and open-field vegetable cultivation. Reported that irrigation technologies form the most adapted sustainable land management tools because irrigation may increase soil fertility with the addition of manure and or more phosphorus that may be added, which are found in irrigation water.

On the other hand, in arid regions, water scarcity has a remarkable role in crop productivity and agricultural activities. Due to the abundance of water or low-cost factors, farmers widely preferred flood or sprinkler methods instead of drip irrigation methods in their practices. However, this irrigation technology is insufficient only to increase productivity in arid and semi-arid regions. Consequently, advanced technologies should be directed to farmers. In regions where water is very scarce, the quantities applied to irrigation through these methods are limited, so crop growth is affected negatively. On the other hand, in the abovementioned regions, the future of food and feed production becomes a serious problem with the increase in the population working in the agricultural sector.

Water scarcity is a significant issue today, especially in agriculture. With growing industrialization and urbanization, cultivation is being affected severely. Modern techniques of irrigation should be practiced for an efficient use of water. Drip irrigation is one of the modern irrigation techniques that is very useful in saving water and fertilizers and reducing labor costs. Improving the existing irrigation methods or finding alternative methods that save water, power, fertilizers, and human labor is necessary. Sustainable and profitable crop production is essential for the development of agriculture as well as for meeting food requirements.

There is substantial evidence that the production of rice has declined in many parts of the world, including major rice-growing countries of Asia, due to less availability of water for irrigation and less productivity of the rice crop. To get the towering yield of rice, a copious supply of water is a pre-requisite. The availability of water for irrigation is not sufficient for the rice crop.

2. Historical Background of Drip Irrigation in Agriculture

Irrigation has a long and complex history in agricultural development (Pardossi et al., 2009). Ancient irrigation systems that include canals and embankments have been found in land terraces and other forms such as groundwater wells and artesian pressure systems. Even in terms of ductile clay pipes, ancient farmers have used a method similar to present-day drip irrigation by making clay pots of different sizes that leak holes at the roots of plants. Continuation, improvements, and modernization of this method can be seen throughout historical development in various parts of the world.

Ancient civilizations such as Mesopotamians, Persians, Egyptians, Chinese, Indians, and Romans established irrigation systems. The Persian underground canals merely affected the ground level and disappeared with the advent of modern surface water transmission systems. Similarly, pot-type underground irrigation systems were practiced by the Chinese to close the spacing of horticulture crops. Among the ancient irrigation systems, the one developed by the Indians and captured in the Arthasastra is historically rich and a scientific methodology of irrigation (Sharma et al., 2018).

Almost two billion hectares of land are currently irrigated, producing 40 % of the world's food (Pardossi et al., 2009). Rapid advances in irrigation technology have occurred in past decades, leading to the development of modern drip irrigation systems which have revolutionized the way water is delivered to crops. Throughout the 1960s and 1970s, many advances were made in crop management, including the development and improvement of center pivot and linear move irrigation systems. Additionally, the design and precision of spray heads and booms were refined, enabling an even water distribution across large areas. Design capabilities were also improved, with the incorporation of computer programs that could derive an irrigation schedule due to input variables. These monumental advances in technology, paired with a better understanding of soil, water, and crop response to irrigation, have greatly increased the efficiency of water used in agriculture. Technological advancements over the past 20 years have formed the foundation of present-day irrigation practices.

3. Importance of Water in Rice Cultivation

Water plays a vital role in agricultural productivity all over the world. Fresh water is essential for life. It is also required for various sectors such as industry, energy and agriculture for economic development. Most ancient civilizations emerged and developed in river basins where water was abundant. For thousands of years, water has been the lifeblood of agriculture to ensure food security. The world population is expected to reach 8.5 billion by 2030, 9.7 billion by 2050 and exceed 11.2 billion by 2100. The ever-growing population will need food and water. In addition to these factors, there is a growing concern about water scarcity due to the increasing competition for shrinking freshwater resources. Globally, agriculture is the largest consumer of water and as the world population grows, the pressure to provide safe and affordable food for all in the face of decreasing water availability will increase further (H. Ali, 2018, M. Sreeman et al., 2018). Therefore, over the past few years, the scientific community has advanced the development of water management and irrigation strategies to enhance crop resilience in low-water environments.

Rice is considered one of the world's most important cereal crops due to its essential value and the area used for cultivation (Setiobudi & Sembiring, 2009). It is a staple food, providing a significant portion of the daily calories of approximately 3.5 billion people, especially in developing countries. Southeast Asia ranks first in the world with 145 million hectares of rice cultivation area.

Rice cultivation requires a significant amount of water compared to other crops. More than 80% of the fresh water resources in Asia are used for agriculture, of which about half of the total irrigation water is used for rice production (Dawe et al., 2003) .It is estimated that up to 3,000 liters of water are needed to produce 1 kg of rice(Satyanarayana et al.,2007). If water is insufficient in rice cultivation, the plant will yield lower yields due to poor root development, limited nutrient uptake, and difficulty in extracting enough water to meet the transpiration needs of the plants. Conversely, if there is too much water, the plants are expected to have limitations in their ability to transpiration as their roots cannot access sufficient oxygen, increasing the likelihood that the nutrients required for plant survival and growth will not be efficiently taken up (Setiobudi & Sembiring, 2009). Irrigation is essential for water conservation and the sustainability of agriculture with the rapid development of new irrigation technologies. Although drip irrigation, which is based on the drip delivery of water close to the root zone of plants, is widely used worldwide (Pardossi et al., 2009), it is used only in a small part of rice-growing areas. Therefore, it is necessary to develop drip irrigation technology specifically adapted to the specific conditions of rice cultivation.

4. Traditional Irrigation Methods

The replacement of traditional flood/furrow irrigation (FFI) by drip irrigation (FFI) is one of the main ways to modernize traditional irrigation systems (Pluquellec, 2002). In the Mediterranean, traditional irrigation systems that have operated stably since ancient times include the irrigated terraced fields of Andalusia (Spain, 711–1492 CE), the Gutta of Damascus (Syria, ca. 2000 BCE), the khettara systems of Tafilalt and Ziz (Morocco, Middle Ages) or the Timimoun oases (Algeria, >1000 CE) (Barceló, 1989, Bianquis, 1989, Lightfoot, 1996, Remini et al., 2011). DI uptake is expected to increase water efficiency, crop yields and irrigation systems modernization in rural areas, ensuring its sustainability in the current context (García-Ruiz et al., 2011, Iglesias et al., 2010, Playán and Mateos, 2006, Wallace, 2000).

From a technological point of view, DI delivers a constant amount of water directly to the plant roots through line sources (emitters) established at or below the soil surface, mostly at low operating pressures (20–200 kPa) and low discharge rates (1–30 l/h) .Since DI uptake requires the removal of hydraulic infrastructure (e.g. channels, basins) and the suspension of some of the tasks associated with traditional irrigation (e.g. fertilization, leveling, ridge and channel maintenance), DI and FI are opposing systems in field applications.

Following the increase in world population, the global demand for crops has increased significantly, leading to a tremendous increase in agricultural practices associated with food production systems. In developing countries, the agricultural sector is the socio-economic sector that employs the majority of the population. Among many crops, rice is one of the most important staple foods chosen for cultivation. It is the staple food responsible for feeding almost half of the world's population, but a large portion of it is grown in a well-planned irrigated ecosystem. Cultivating rice with the following traditions requires a significant amount of water (Dattatraya Vibhute et al., 2017). Rice can be produced in both rain-fed upland and lowland rain-fed ecosystems, but most rice is produced through flood irrigation, most often through some form of irrigation system. The age-old tradition of rice cultivation practiced by many rice farmers uses surface and flood irrigation; water is applied directly to the foot of each plant or ridge on which the plant is grown. Various types of conventional irrigation practices such as Border, Furrow and Basin Irrigation Systems (e.g. Control, Wild Flood, Ridge Bed, Conventional Bed) are widely used in rice farming to achieve maximum yield. These conventional methods are old practices with some cultural backgrounds and are a vital part of local food production techniques. Direct irrigation to the plant or ridges is a centuries-old design created by farmers, which is low cost but has a very low water use efficiency gamma (γ) level ranging from 20-30%. As climate and agricultural practices have evolved, irrigation methods have also advanced, starting with basic furrow irrigation and moving to flood type methods commonly used to apply water to the fields. Continuous flood is the most commonly used irrigation method in the world's major rice producing countries. Generally, water flows evenly along the toe of the plant ridges and is evenly distributed throughout the field. This conventional practice not only wastes time and energy, but also 30-40% of the applied water is lost through infiltration or runoff. More water left in the field for 6-10 days during the peak crop season also results in more weeds in the field. The practice requires manual labor as workers have to push water to each location along the length of the field up to 5 times per crop. Of all irrigation requirements, plant or ridge irrigation is known to be one of the weakest systems. This results in huge water losses either through runoff or direct evaporation from stagnant water at the foot of the crop ridges. This age-old irrigation process, which has been practiced for decades in many food basket areas around the world, is well known and regularly and timely applied.

5. Benefits of Drip Irrigation in Rice Cultivation

Drip irrigation in rice cultivation offers various benefits:

a) Improved water efficiency—less water is used while maintaining the same yield level;

b) Less weed growth—their growth is more restricted due to precise watering, so the amount of herbicides required is also less;

c) Better crop health—consistent moisture reduces plant stress, damp conditions decrease the severity of rice blast, and steady moisture levels result in greater grain quality with less chalkiness;

d) Money savings—as a result of the matters mentioned above, cost savings for farmers include water, herbicides, and health remedies, in addition, higher or more stable production means more revenues as well;

e) Reduced runoff due to controlled water applications-in contrast, drought events are more severe in fields with traditional irrigation;

f) Enhanced production—a number of further test results have shown that drip irrigation can increase rice yields, both the filled grain percentage and 1000-grain weight is higher, moreover, drip fertigation (along with special fertilizers that will not clog the emitters) can boost yields immensely (Setiobudi & Sembiring, 2009). At the same time, the nutrients it provides are utilized more efficiently, so leaching is significantly reduced. Furthermore, drip irrigation has been proven to promote higher rice production in areas with insufficient water resources (Manuel Gonçalves et al., 2022), and thus, this technology could help farmers weather changes due to global warming. Besides climate change, progression in society is also a threat to food safety; population growth and the swift expansion of urban areas lead to continuous land degradation. Balancing these threats and demand for heightened production is not an easy task by any means. All in all, the real-life application of these benefits may differ, but they form a key foundation for understanding drip irrigation's influence on sustainability and production.

6. Challenges and Limitations of Drip Irrigation in Rice Cultivation

Though drip irrigation has immense potential to improve water efficiency and productivity, its implementation in rice is surrounded by numerous challenges and constraints.

a) In comparison to flooding irrigation and low lift pump sprinkler systems, the initial investment cost of drip systems is significantly higher, which is inevitable for their effective operation. This higher capital cost outlay can deter farmers from installing such systems at their farms, especially resource-poor farmers.

b) A drip system requires technical knowledge of its components and proper system installation, operation, and maintenance. Farmers without this technical know-how may feel uncomfortable using such technologies (Belder et al., 2007).

c) Emitters and filters are the basic components of a drip irrigation system. Emitters are prone to clogging due to suspended matters, which affects water discharge from the emitters. Besides emitters, clogging could also occur in filters, valves, tubes, and screens due to organic and inorganic particles present in irrigation water. Once the filters and emitters are damaged due to clogging, the cost of repairing or replacing them is not economical for resource-poor farmers.

d) Unlike the other irrigation methods, drip irrigation is a capital-intensive technology and it requires frequent maintenance throughout the irrigation season and after the harvest. An interruption in the water flow damages the crop by creating dry and wet patches within the field. Therefore, a regular inspection of on-farm devices is necessary (Nkya et al., 2015).

e) Drip irrigated water is not only sensitive to the soil and crop but it is also sensitive to climatic factors. Low humidity and high temperature in the drip irrigated field increase the evaporation loss of water.

f) Dry wind affects the uniformity of water applied to the crops by moving the droplets away from the target area. Rain with high intensity and wind speed could damage the drip irrigation system. On the other hand, high frequency and intensity rain reduces the requirement for supplementary water and affects the system's optimum scheduling.

Therefore, water for a drip system should be managed considering both crop water requirements and other agro-physical conditions of the crop-growing environment. Since the potential for expansion is high, especially in water-scarce areas, there should be more support and incentives from the government to overcome these physical and awareness-related constraints. Similarly, more research on crop suitability and emission devices is warranted areas.

Many Asian countries are experiencing a water crisis due to increasing needs for food production; water availability is now closely associated with food security. To counteract this potential water crisis, China intends to execute irrigation facility replacement and improvement in order to efficiently manage irrigation water. For sustainable management of irrigation water, one potential alternative approach for states is the drip irrigation technique instead of surface or overhead irrigation systems. Many efforts in this direction are made in various agricultural land irrigations, but freshwater rice land irrigation is a function of maintaining a water layer in which rice obfuscates air inputs. Thus, air penetration in the field is impeded.

Drip irrigation offers a positive alternative to typical rice irrigation. Drip irrigation could offer spatial and temporal management advantages compared to surface irrigation for rice. To enhance social well-being and strive to create sustainability in rice agriculture, opportunities for drip irrigation in rice cultivation were addressed. Moreover, drip irrigation has advantages in growing other crops in rotations, which could be an additional option, particularly in relatively large farms. This could be extremely vital in countries where water has been scooped up and large farms are seeking to expand the value of crops produced. However, existing limitations restricted the popularization of drip irrigation for rice cultivation. This raises a number of challenges for drip irrigation adoption on a wide scale that refers to the research interest. The challenges faced in the conversion of traditional rice cultivation techniques to modern agriculture are comprehensive. There are engineering challenges, issues of the environment, and the mindset of farmers.

7. Initial Investment Costs

Many farmers in various parts of the world, especially in Indonesia, still use manual irrigation systems - an outdated and labor-intensive method. Another issue in the field is that the water level is not equal throughout the field. The soil in the rice fields is not flat. If it is not leveled properly, some of the rice may dry out due to evaporation of water and water seeping into areas outside the field. The current traditional irrigation system uses surface irrigation, which causes high evaporation. This cultivation method will increase the amount of weeds in the rice plants. The growth of the rice plants will be inhibited due to the rise of the water and the covering of the upper part of the plant with water (Wilbourn, 2013). To overcome these difficulties, rice irrigation should be done automatically and efficiently. The initial investment cost of drip irrigation is usually high, and farmers, especially small farmers, are reluctant to adopt it. However, the focus should be on switching to a more efficient irrigation system for rice cultivation. A non-stationary economic model of the yield response factor to water input was derived and used to evaluate the net benefits of a hypothetical drip irrigation adoption strategy for a canal-based irrigation system in the Ayeyarwady Delta, Myanmar. The capital costs of the hypothetical adoption strategy included the costs of pump installation, filter installation, lateral lines, drip irrigation pipes, and unskilled labor costs for excavation and filter cleaning. More financially viable drip irrigation adoption strategies could include portable drip irrigation systems or other configurations, including non-canopy drip irrigation methods. Mobile subsidies, financing, and assistance in switching to front-panel or multi-line drip irrigation by government and non-governmental organizations could accelerate the adoption of more financially viable drip irrigation adoption strategies. It is important for both farmers and stakeholders to keep in mind that investing in sustainable irrigation practices can result in beneficial long-term economic returns. The initial investment costs associated with switching from traditional flood or furrow irrigation to drip irrigation appear to be one of the largest individual risk factors for farmers that may limit adoption. When considering the ease of access to drip irrigation equipment, the cost of the kit, including the pump, filtration system, piping, and proper installation of these components, should be taken into account. In the context of a small-scale upland farming operation from the Kilimanjaro region, the cost of a complete system that can effectively irrigate 1 acre of land ranges from $1000 to $3000 (Nkya et al., 2015). Although initial investment costs can be a barrier to switching to efficient irrigation methods, it is emphasized that long-term costs are generally lower, and total profits are often greater compared to traditional methods. For example, in the Lower Rio Grande Valley in the United

States, investment in a drip irrigation system pays for itself through seed, labor, and water savings as well as increased fruit yields (Wilbourn, 2013). Given the potential for drip irrigation to significantly increase water efficiency and, generally, yields, it is critical to increase awareness of how the payback period for the systems can be achieved. In the context of net return cash flow analysis in this region, it has been shown that producers can recoup their capital investment after 5 to 10 cropping seasons. Providing access to grants or microcredit loans for those wishing to switch to drip farming can facilitate a quicker transition and buffer the high initial costs that farmers must invest in one go.

8. Drip Irrigation Adoption in Rice-Growing Regions

Drip irrigation has traditionally been associated with high value crops such as fruit, grapes and cotton. However, recent trials have shown that it can also be used in rice production - with very significant water savings. In addition, the increasing scarcity of water resources has led to long-term water use regulations in some south-east Asian countries and a shift in emphasis towards improving the efficiency of water use. A drip irrigation system placed along crop rows uses between 0.2-0.300 m^3 of water per hectare (Belder et al., 2007).

With the shift of farmers who grow rice from classical paddy cultivation to the drop irrigation system, the loss of irrigation will decrease and will be saved between 23 % and 50 % of the amount of water used in cultivation (Howell et al., 2015).

Currently, more data is needed about the rate and location of real demand for irrigation technologies that save water. The perceptions of the farmers to adopt drop irrigation vary depending on cultural and economic contexts. Because the technology is inadequate and drip irrigation request is still more expensive than the widespread irrigation system is still located. However, especially young breeders switch to drop irrigation system faster.

Like never before, fresh water has become crucial for agricultural activities around the world; facing this challenge, improving water management is no longer an alternative. Growing needs for food production due to an expanding population and increased water scarcity because of continuous pollution and global warming have posed water management as one of the most critical problems in many places on the Earth.

9. Future Prospects and Innovations in Drip Irrigation Technology

Most of the countries in the South Asian region are agriculture dependent and scarcity of irrigation water for cultivation is a common phenomenon. There is an increasing interest to adopt new crops, cultivation methods and technologies for increasing crop yield. Drip irrigation is a new technology in these countries requiring less amount of water. It is well known that almost 90% of the root zone can be exploited when water and nutrients are delivered using Drip Irrigation Systems (DIS) . Also small amount of water can be directly supplied to the root zone by Drip Irrigation Pipe (DIP). Rice is a major food crop in these countries. The aim of this research is to suggest better water distribution pattern and arrangement of DIP for maximizing crop yield in rice cultivation. Improving crop yield and decreasing consumption of water are the need of the time. In the extensive experimental work presented here, a completely new micro layout has been developed. In the developed micro layout rice cultivation performed effectively using Drip Irrigation Pipes (DIP). Conversely, results show that the functionality is lower in traditional practice.

The following emerging trends and advancements in drip irrigation technology that have the potential are promising for maximizing crop yield in cultivation and enhancing efficient use of water are reported next. The smart drip irrigation technology refers to a system that helps farmers manage their respective drip irrigation system that eventually makes the system intelligent. Various factors for making the system smart are discussed. The main emphasis is on the potential research and development of the drip irrigation technology. That highlights the research trend in smart drip irrigation. The existing and smart technologies in the detection of soil moisture for irrigation based on the use of different devices and sensors as well as automation of the control system also be presented. After the smart drip irrigation technologies, a framework or structure for the development or design of workers for smart drip irrigation and automation of in-field operations. A strong emphasis on future perspectives is made that advances would give the potential for smart drip irrigation for widespread use in different crops and cultivation practices. As such, the adaptive drip irrigation and also the irrigation scheduling method for more deeply studied to help farmers for frequent irrigation practices, increase crop yield, and improve water efficiency. Emerging trends promote the latest information to develop more advanced and efficient drip irrigation equipment and materials that can be used in the adaptiveness and scheduling while maintaining the adoption and sustainability of the practice. Furthermore, water resources situation for the cultivation is worsening and reflects on new drip irrigation practices and scheduling is predicted to adapt to future situation against challenges, opportunities and constraints.

The 21st century is the age of technology and speed. The emerging technologies have brought a revolution in every field. Drip irrigation coupled with a device that senses the availability of moisture and automatically applies the desired amount of water at the required time is relatively new in the field of agriculture compared to the local irrigation systems which have been in use for quite a long time. Currently proposed to enhance the implication of modern drip irrigation systems, would allow recording advantages and span the range of issues related to crop growth. The modern irrigation system could be computer-controlled through special software, capable of adjusting water automatisms within the set of critical environmental conditions for the growth of crops. In the creation of modern irrigation systems, of advanced technology, a very significant role to be played by predicting the rising demand for irrigation markets, to analyze drive forces and implement an adapted perspective policy (Porras Binayao et al., 2024).

Perhaps no two words more aptly describe the state of today's agriculture and no two words are more ominous to agriculture's ability to meet the increasing demand for food and fiber, than "sustainability" and "irrigation". This is unfortunate and may well be undeserved. There are many reasons for the undeserved reputation of unsustainability when it comes to irrigation. First and foremost is the rapid rate of innovation and new technologies being incorporated in irrigation systems. Innovations come in new material for parts and pipes, sprinkler packages with flow triggering intensity, or changes in water conveyance. Design of water irrigation systems, particularly in developing countries, are inconsistent with crop water requirements which mean over-irrigation, with quantified losses of tens of water and energy. Since the water supply is the same for both countries, only the increase of crop evapotranspiration or the indirect decrease in the production and food chain, leads the countries to their optimum irrigation path. In either scenario, possible sustainability is directly related to changes in irrigation practices. Furthermore, the innovation in material means that the irrigation networks when it's getting older facing loss of pressure and as a result reduction in the area that the water passes, creating system failures.

Though design and on-farm performance often fall short of expectation, new, more-precisely designed systems can be very water conserving. Aside from equipment factors, there are many policy trends that are leading toward the more efficient use and management of water resources in agriculture. These trends involve political agendas both domestically and abroad and are directly likely to influence irrigation practices in the future. Finally, a critical analysis of the inevitability of the continuation of the problem of unsustainable irrigation development and practice and some observations are provided regarding the likely future. Overall, these systems may prove innovative, encourage adoption and enhance the sustainability of future systems. Will collaborate with an array of interested parties to develop even better systems and of necessity better strategies in the management of irrigation technology.

To summarize the issue briefly, the problem of water scarcity is one of the most important problems of today's world, and therefore it is of great importance to use water efficiently, including the cultivation of rice fields. Rising economies such as India are known for their different and specific features in water resources management. On the one hand, there is an evolution in the use of innovative and high -tech methods in water resources management. This enabled India to overcome the famine in the water sources to a certain extent. Meanwhile, there are opposite characteristics in various regions of India to the successful adoption of water management practices. In recent years, the Indian economy has witnessed a huge increase in the adoption of drop irrigation practices, especially in rice fields.

Rice fields can be efficiently irrigated by using the integrated drop irrigation system with fertilization. Rice is famous for its dense water, so significant amounts of water require water to irrigate the fields.

References

Barceló., M. (1989). El diseño de espacios irrigados en al-Andalus: un enunciado de principios generales, L. Cara Barrionuevo (Ed.), El Agua En Zonas Áridas. Arqueología E Historia. Actas Del I Coloquio de Historia Y Medio Físico, I, Instituto de Estudios Almerienses, Almería,15-47

Belder, P., Rohrbach, D., J Twomlow, S., & Senzanje, A. (2007). Can drip irrigation improve the livelihoods of smallholders? Lessons learned from Zimbabwe:Global Theme on Agroecosystems Report no. 33. *International Crops Research Institute for the Semi-Arid Tropics*, Bulawayo, Zimbabwe. https://oar.icrisat.org/2386/

Bhasker, P., Singh, R.K., Gupta, R.C., Sharma, HP, Gupta, PK. (2018). Effect of drip irrigation on growth and yield of onion (*Allium cepa L.*). *J. Spices and Aromatic Crops*, Vol. 27 (1): 32-37

Dattatraya Vibhute, S., Sarangi, A., K. Singh, D., K. Bandhyopadhyay, K., S. Parihar, S., & Kumar, D. (2017). Comparative evaluation of water budgeting parameters under different rice (*Oryza sativa L.*) cultivation methods. *J. App.and Nat. Sci.* 9 (3):1373-1380 DOI: 10.31018/jans.v9i3.1370

Dawe, D., Dobermann, A., Ladha, J.K., Yadav, R.L., Lin, B., Lal, P., Panaullah, G., Sariam, O., Singh, Y., Swarup, A., Zhen, Q.X. (2003): Does organic matter improve the sustainability and profitability of intensive rice systems. - Field Crops Res. 83:191- 213.

García-Ruiz, J.M., López-Moreno, J.I. . Vicente-Serrano, S.M. , Lasanta–Martínez, T. , Beguería, S. (2011).Mediterranean water resources in a global change scenario, *Earth-Science Rev.*, 105, 121-139

H. Ali, M. (2018). Drought Screening and Supplemental Irrigation Management for some Rice Cultivars in Drought Prone Area of Bangladesh. *Int. J. App. Sci.* 1(2), 107-116 DOI: 10.30560/ijas.v1n2p107

Howell, KR., Shrestha, P., C. Dodd, I. (2015). Alternate wetting and drying irrigation maintained rice yields despite half the irrigation volume, but is currently unlikely to be adopted by smallholder lowland rice farmers in Nepal. *Food and Energy Security*, 4(2),1-4, DOI: 10.1002/fes3.58

Iglesias, A., Mougou, R., Moneo, M., Quiroga, S.(2010). Towards adaptation of agriculture to climate change in the Mediterranean, *Reg. Environ. Chang.*, 11, 159-166.

Lightfoot., L. (1996). Moroccan khettara: traditional irrigation and progressive desiccation, *Geoforum*, 21:2, 261-273.

M. Sreeman, S., Vijayaraghavareddy, P., Sreevathsa, R., Rajendrareddy, S., Arakesh, S., Bharti, P., Dharmappa, P., & Soolanayakanahally, R. (2018). Introgression of Physiological Traits for a Comprehensive Improvement of Drought Adaptation in Crop Plants. *Frontiers in Chemistry*, 6:92,1-2, DOI: 10.3389

Manuel Gonçalves, J., Nunes, M., Ferreira, S., Jordão, A., Paixão, J., Eugénio, R., Russo, A., Damásio, H., Maria Duarte, I., & Bahcevandziev, K. (2022). Alternate Wetting and Drying in the Center of Portugal: Effects on Water and Rice Productivity and Contribution to Development. _*Sensors*, 22, 3632 DOI: 10.3390/s22103632

Nkya, K., Mbowe, A., & H.J.R. Makoi, J. (2015). Low - Cost Irrigation Technology, in the Context of Sustainable Land Management and Adaptation to Climate Change in the Kilimanjaro Region. *J. Envir.Earth Sci.*5(7), 45-56.

Pardossi, A., Incrocci, L., Incrocci, G., Malorgio, F., Battista, P., Bacci, L., Rapi, B., Marzialetti, P., Hemming, J., & Balendonck, J. (2009). Root Zone Sensors for Irrigation Management in Intensive Agriculture. *Sensors*, 9, 2809-2835; DOI:10.3390/s90402809

Playán, E., Mateos, L. (2006). Modernization and optimization of irrigation systems to increase water productivity, *Agric. Water Manag.*, 80, 100-116.

Pluquellec, H. (2002). How Design, Management and Policy Affect the Performance of Irrigation Projects -emerging Modernization Procedures and Design Standards, FAO regional office for Asia and the Pacific, Bangkok, Thailand.

Porras Binayao, R., Vincent Lagapa Mantua, P., Rose May Pardillo Namocatcat, H., Kachel Klient Bocboc Seroy, J., Ruth Alithea Bacotot Sudaria, P., Migan Vincent Casicas Gumonan, K., & Mae Malbas Orozco, S. (2024). Smart Water Irrigation for Rice Farming through the Internet of Things. *Int. J.Computing Sci.Research*_8:2550-2563 DOI: 10.25147/ijcsr.2017.001.1.172

Rao, K. V. R., Gangwar, S., Keshri, R., Chourasia, L., Bajpai, A., Soni, K.(2017). Effects of drip irrigation system for enhancing rice yield under system of rice intensification management, *App. Ecology and Environmental Research,* 15(4):487-495.

Remini, B., Achour, B., Albergel, J.(2011). Timimoun's foggara (Algeria): an heritage in danger, *Arab. J. Geosci.*, 4, 495-506.

Satyanarayan, A., Thiyagarajan, T.M., Uphoff, N. (2007). Opportunities for water saving with higher yield from the system of rice intensification, *Irrigation Science,* 25:99-115.

Setiobudi, D. & Sembiring, H. (2009). Increasing water productivity of lowland rice through the water saving techniques and crop management in response to drought. *Agromet*, 123-147, DOI: 10.29244/j.agromet.23.2.123-147

Wallace, J., (2000). Increasing agricultural water use efficiency to meet future food production,Agric. Ecosyst. Environ., 82, 105-119.

Wilbourn, B. (2013). Economic Analysis of Alternative Irrigation Technologies: Texas Lower Rio Grande Valley. https://oaktrust.library.tamu.edu/items/91d6aadf-e533-41bc-919d-cbafce86fb43

Chapter 2

CLIMATE-RESILIENT IRRIGATION STRATEGIES FOR SUSTAINABLE COTTON PRODUCTION: ADAPTING TO WATER SCARCITY AND ENVIRONMENTAL CHANGE

Burçak KAPUR[1], Uğur KEKEÇ[2]

1 Prof.Dr.University of Cukurova, Faculty of Agriculture, Department of Agricultural Structures and Irrigation, Orcid no: 0000-0001-6131-4458.
2 Öğr.gör.Dr., University of Cukurova, Yumurtalık Vocational School, Department of Plant and Animal Production. Orcid no: 0000-0003-1321-9135

1. Introduction

Among the most pressing problems facing agriculture globally today is water scarcity, particularly in arid and semi-arid regions where water use efficiency is critical for sustainable crop production. Cotton (Gossypium hirsutum L.), which is an important industrial crop as well as an economic crop, is highly water-sensitive in spite of its relative tolerance to water stress. Optimum irrigation management is, therefore, critical for maintaining productivity while conserving water. The research discussed in this chapter collectively highlights the contribution of deficit irrigation, advanced irrigation techniques, and technology in improving water use efficiency and sustaining cotton yields under varying climatic conditions.

Deficit irrigation is a promising strategy for mitigating the impact of water scarcity by deliberately using less water than the crop requirement at particular growth stages. Several research works have established that deficit irrigation can be used to increase water productivity, although its effect on the yield of seed cotton varies greatly with the type of the soil, climatic conditions, irrigation method, and planting density. A global meta-analysis by (Cheng et al, 2021) revealed that deficit irrigation increased water productivity by 5.3%, while it caused an average loss in yield of 20.2% when it was applied throughout the whole period of cotton growth. However, when it is adjusted to the crop growth stages, climatic conditions, and the type of the soil, deficit irrigation can cause very minimal loss in yield while significantly improving water use efficiency.

There have been various strategies for optimizing cotton irrigation production in the last few years of research. (Wu et al, 2024) conducted a three-year field trial in China's Xinjiang region wherein the effect of deficit irrigation in combination with high planting density was examined. Their finding was that with water-limited conditions, higher planting density stabilized the cotton yield while reducing irrigation water input by 20%. This was made achievable by improving the interactions between the roots, the soil, water, and nitrogen, which ultimately increased water productivity. Along the same line, (Du et al, 2024) simulated irrigation scenarios using the AquaCrop model and found varying irrigation frequencies and amounts with historical meteorological data significantly improving the performance of the yield as well as water efficiency in the region of Southern Xinjiang.

Another significant factor influencing the success of deficit irrigation is the irrigation system type. (Shukr et al, 2021) compared the performance of the drip, sprinkler, and furrow irrigation systems under deficit irrigation conditions and found drip irrigation to be the most water-efficient with the highest water use efficiency while maintaining the cotton yield at its optimum. Their simulation study revealed the application of the subsurface drip irrigation, in turn, to sustain high yields at the levels of 60–80% of full irrigation, which can be an effective strategy for water-limited regions. (Further, Xu et al, 2024) performed a meta-analysis of drip irrigation with plastic mulch, which revealed the latter to increase water retention while reducing evapotranspiration loss, thus maximizing overall irrigation efficiency.

Another important area of sustainable cotton irrigation is the interaction between the properties of the soil and irrigation management. (Zhangjin et al, 2025) analyzed the economic and agronomic effects of deficit irrigation in different types of soils and confirmed that silt loam soils preserved water in deficit irrigation conditions, thereby reducing loss in yield compared to sandy soils. Their study emphasized the necessity of embracing site-specific irrigation practices in accordance with the properties of the soil to maximize productivity while conserving water resources.

Improvement in irrigation management has also been facilitated by technological advancements. The application of precision agriculture, remote sensing, and unmanned aerial systems (UAS) in optimizing irrigation scheduling was emphasized by (Adeleke 2024). The technologies facilitate real-time monitoring of the environment, crop water stress, and soil moisture, which helps the farmer in the efficient application of water. In addition, decision support systems such as DSSAT and CROPGROW-DSSAT have been applied in the simulation of irrigation strategy and predicting the response in yield, providing effective tools for enhancing water use efficiency.

Although deficit irrigation presents a promising water-saving approach, it must be controlled carefully in order to avoid excessive yield loss. (Lin et al, 2024) examined the effects of different levels of deficit irrigation during the critical flowering and boll-set phases of cotton and found that the application of 90% of the regional irrigation standard maintained high yields while conserving water. Their findings suggest that a slight reduction in water application at critical growth phases can significantly elevate the level of sustainability while maintaining cotton production.

Generally, the work presented in this chapter offers a comprehensive overview of the opportunities and challenges associated with deficit irrigation in cotton cultivation. Cotton growers can reconcile water conservation with profitable yields through the integration of optimal irrigation regimes, innovative irrigation technology, and precision management approaches. The knowledge generated through such research work sustains the ongoing pursuit of creating sustainable farming approaches for countering the issues created by water scarcity in cotton-growing regions of the world.

2.Effective Approaches for Water Management in CottonProduction

Water management is significant in sustainable cotton production, particularly in arid and semiarid regions with limited water availability. The preservation of cotton yields with efficient irrigation management is needed for improving water use efficiency. Various research works have illustrated how deficit irrigation, new irrigation technologies, soil management practices, and precision agriculture technologies can be applied to improve water productivity significantly. The most effective water management practices for cotton production are presented in this section in the context of the most recent scientific research.

2.1.Deficit Irrigation Strategies

Deficitirrigation is a recognized technique for optimizing water use through the application of less water than the crop demands at particular growth stages. A study by (Cheng et al, 2021) revealed that deficit irrigation increases water productivity by 5.3% while reducing the yield of seed cotton by 20.2% when applied through out the growth season. Strategic deficit irrigation, howeversuch as limiting water cutback to the vegetative stage o rimplementing partialroot-zone drying prevent loss in yield while optimizing water use efficiency. (Wu et al, 2024) found that deficit irrigation with high planting density in Xinjiang, China, stabilized the yield while reducing their rigationinputby 20%. The approach enhances the root development and water-nitrogen distribution in the soil, leading to better water absorption and higher water productivity.

2.2. Advanced IrrigationSystems

The choice of the irrigation system is of great importance in water management. Drip irrigation has been largely recognized as the most efficient strategy for cotton cultivation, particularly in water-scarce regions. (Shukr et al, 2021) compared the performance of drip, sprinkler, and furrow irrigation under deficit irrigation condition sand found that SDI maintained high yields with 60–80% full irrigation. Similarly, (Xu et al, 2024) demonstrated drip irrigation with plastic mulch significantly increased water conservation, reducinge vapor transpiration loss while enhancing the stability of cotton yield. Inaddition, precision irrigation methods likevariable rate irrigation (VRI) enable tail or edwaterapplication depending on the level of soil moisture, climatic conditions, and crop growth stages. The Aqua Crop model, applied by (Du et al, 2024), was able to optimize irrigation scheduling for various climatic conditions in a manner that provided maximum water efficiency while maintaining yields.

2.3. Soil andCrop Management Practices

Soil management is important in water conservation. Soil water retention can be increased by the use of suitable a mendments, mulching, and croprotation, there by lowering there quirement for irrigation. (Zhangjin et al, 2025) high lighted in their research that silt loams oil sarepreferable for deficit irrigation compared to sandy soils because of their higher water-holding capacity. The use of organic matter and conservation tillage can also increase the structure of the soil, lowering the surface runoff and enhancing the infiltration. Furthermore, planting density adjustments and cropselection are required. High-density planting, which (Wu et al, 2024) studied, increases the overlap of the roots, which increases water uptake in thes oil as well as reduces water competition. Also, (Lin et al, 2024) confirmed that the adjustment of irrigation schedules in line with the cotton growth cycles can increase water use efficiency, with the most critical growth stages receiving the necessary moisture.

2.4.Precision Agriculture and Technology Integration

Innovation in technology has transformed water management in cotton farming. Remote sensing, drones, and soil moisture sensors providereal-time data for optimizing their rigation schedules. Adeleke (2024) high lighted the use of precision agriculture in reducing water was stage by monitoring crop water stress and adjusting the irrigation accordingly.

Farmers can utilize decision support systems such as DSSAT and CROPGROW-DSSAT to simulate various irrigation strategies, predicting they yield response under varying water conditions. The data-based strategy ensures precise application of water with minimal was stage while maintaining the productivity of cotton. Optimal water management in cotton cultivation requires the integration of deficit irrigation strategies, advanced irrigation technology, conservation agriculture, and precision agriculture technology. By implementing site-based irrigation schedules, adopting water-saving irrigation systems, and integrating in novative technology, wateru sage can be optimized while ensuring high yields. With water scarcity continuing to affect agriculture globally, adopting such science-based strategies will be critical in ensuring the long-term sustainability of cotton cultivation.

3.Evaluating the Effect of Deficit Irrigation on Yield and Water Use Efficiency of Drip Irrigation Cotton

Deficit irrigation has emerged as a water-savingstrategy in cotton production, particularly in arid and semiarid regions with scarce water supply. The technique is the application of irrigation at a rate below the full crop water requirement with the water stress regulated while maintaining the yield at acceptable levels. Drip irrigation, which is a highly efficient water application technology, contributes to the water use efficiency by minimizing waterloss by evaporation and runoff. This section discusses the impact of deficit irrigation on cotton yield and water productivity with dripirrigation, with lessons learned from the most recent research.

3.1.Impact of Deficit Irrigation on Cotton Yield

The effect of deficit irrigation on cotton yield varies with irrigation levels, timing, and the environment. A meta-analysis by (Xu et al, 2024) compared water use efficiency and cotton yield response to different levels of deficit irrigation. The results indicated little decrease in yield by deficit irrigation at the range of 80-100% of full irrigation (FI), while below 60% FI significantly decreased cotton yield. (Wu et al, 2024) demonstrated how deficit irrigation with high planting density can compensate for the yield loss by increasing the interactions among root-soilwater-nitrogen. Their study indicated that maintaining the planting density at 22.5 plants/m^2 in deficit irrigation conditions increased the stability of the yieldby 9.2–23.5% relative to low densities. Similarly, (Lin et al, 2024) confirmed that the use of 90% of the local irrigation standards preserved cotton yields while saving water.

3.2.WaterUseEfficiency Enhancement

Water use efficiency (WUE) is a key parameter in evaluating deficit irrigation strategies. Studies indicate that deficit irrigation improves WUE by reducing excess water application while maintaining crop productivity. (Xu et al, 2024) reported a 7.39% increase in WUE under deficit irrigation compared to full irrigation. Similarly, (Zhangjin et al, 2025) observed that silt loam soils exhibited higher WUE than sandy soils, highlighting the importance of soil type in deficit irrigation management. (Shukr et al, 2021) compared different irrigation systems and found that subsurface drip irrigation (SDI) was the most effective method for optimizing WUE, maintaining high yields even under 60–80% FI. Furthermore, (Adeleke ,2024) emphasized the role of precision agriculture in enhancing WUE, with real-time soil moisture monitoring allowing for more precise water application.

3.3. Drip Irrigation and Deficit Irrigation Synergy

Drip irrigation plays a crucial role in the success of deficit irrigation by delivering water directly to the root zone, reducing waste. Research by (Du et al, 2024) utilizing the Aqua Crop model demonstrated that optimized drip irrigation scheduling significantly improved WUE while maintaining yield levels. (Xu et al, 2024) further showed that combining drip irrigation with plastic mulch reduced evapotranspiration losses, improving both yield and WUE. The effectiveness of deficit irrigation under drip irrigation systems is also influenced by irrigation frequency. (Lin et al, 2024) found that adjusting irrigation intervals to 12 days during the flowering and boll-setting stages optimized WUE without significantly reducing yield. This finding suggests that irrigation timing and scheduling are critical factors in maximizing the benefits of deficit irrigation.

Deficit irrigation, when applied strategically under drip irrigation systems, can enhance water use efficiency while sustaining cotton yields. Research indicates that maintaining irrigation at 80–100% FI optimizes yield retention, while lower irrigation levels significantly impact productivity. Combining deficit irrigation with high planting density, precision agriculture technologies, and advanced drip irrigation techniques can further improve efficiency. As water scarcity becomes an increasing challenge, adopting scientifically backed deficit irrigation strategies will be essential for the sustainable production of cotton in arid regions.

4.Management of IrrigatedCotton in Context of Climate Change

Climate change poses a significant challenge to global cotton production, affecting yield stability, water availability, and overall crop management. Rising temperatures, altered precipitation patterns, and increasing occurrences of extreme weather events necessitate innovative irrigation strategies to sustain cotton yields. Given cotton's dependence on water, particularly in arid and semi-arid regions, effective water management is essential to mitigate the adverse impacts of climate change. This section explores the key challenges posed by climate change and presents adaptive irrigation strategies for managing irrigated cotton production effectively.

4.1.Climate Change Impacts on Cotton Irrigation

Climate change influences cotton production through rising temperatures, changing precipitation patterns, and elevated atmospheric CO_2 levels. Studies indicate that: Temperature Increase: Higher temperatures can shorten the cotton growing season, reducing the time for fiber development and ultimately affecting yield and quality (Li et al, 2021). Research suggests that every 1°C increase in average temperature can decrease cotton yield by 1.64% (Jans et al, 2021). Altered Precipitation Patterns: Variability in rainfall affects soil moisture availability, increasing reliance on irrigation. Rainfed cotton is particularly vulnerable to changing precipitation trends, with potential yield declines of up to 30% in extreme climate scenarios (Ahmed et al, 2023). CO_2 Fertilization Effect: Elevated CO_2 can enhance cotton growth by improving photosynthesis and water use efficiency. However, these benefits may be counterbalanced by increased evapotranspiration demands due to rising temperatures (Wang et al, 2022).

4.2. Adaptive Irrigation Strategies for Sustainable Cotton Production

To mitigate the risks associated with climate change, several irrigation management strategies have been proposed:

4.2.1.Deficit Irrigation for Water Conservation

Deficit irrigation involves applying water below full crop water requirements at specific growth stages to enhance water use efficiency. Studies indicate that:

- Maintaining irrigation at 80–90% of full irrigation can sustain yield while reducing water consumption by 10–20% (Gui et al, 2023).

- Stage-specific deficit irrigation, particularly during the vegetative phase, minimizes yield loss while optimizing water use (Rahman et al, 2018).

- Soil moisture monitoring tools can help fine-tune irrigation schedules to avoid excessive stress on cotton plants (Shikha et al, 2022).

4.2.2Drip Irrigation and Plastic Mulching

Drip irrigation is one of the most efficient methods for delivering water directly to the root zone, reducing evaporation losses and enhancing cotton productivity. Research highlights that:

- Drip irrigation combined with plastic mulching increases soil moisture retention, improving yield stability under heat stress (Wang et al, 2022).

- Subsurface drip irrigation (SDI) further reduces evaporation losses and ensures uniform water distribution, particularly in sandy soils (Zhang et al, 2016).

4.2.3. Precision Irrigation Technologies

Technological advancements enable real-time monitoring of soil moisture and weather conditions, allowing for precise irrigation applications. Key approaches include:

- Remote sensing and satellite-based irrigation scheduling to optimize water application based on real-time crop stress indicators, (Ahmed et al, 2022).

- Decision support systems (DSS) and crop modeling tools, such as DSSAT and AquaCrop, for forecasting irrigation needs under different climate scenarios, (Hussein et al, 2020).

- Automated irrigation systems integrating weather and soil data to deliver optimal water amounts, reducing overuse and improving efficiency, (Schaphoff et al, 2018).

4.3. Soil and Crop Management for Water Retention

Improving soil health and adopting climate-resilient cotton varieties can enhance water retention and reduce irrigation demands. Strategies include:

- Soil amendments and conservation tillage to increase organic matter and soil moisture retention (Rehman et al., 2019).

- Drought-resistant cotton cultivars that exhibit higher water-use efficiency and tolerance to heat stress (Farooq et al., 2021).

- Cover cropping and intercropping to reduce soil evaporation and improve overall water conservation in cotton fields (Gui et al., 2023).

4.4.Future Directions and Policy Recommendations

The integration of climate-adaptive irrigation practices requires coordinated efforts from researchers, policymakers, and farmers. Recommendations include:

- Investment in water-saving irrigation infrastructure, particularly in regions vulnerable to climate change.

- Incentives for farmers to adopt precision irrigation technologies, including subsidies for soil moisture sensors and automated irrigation systems.

- Climate-resilient agricultural policies that promote water-efficient cropping systems and sustainable land management.

- Enhanced research on climate-smart cotton farming, focusing on region-specific adaptation strategies and new irrigation techniques.

Climate change poses significant challenges to irrigated cotton production, but adaptive irrigation strategies can mitigate its adverse effects. By implementing deficit irrigation, adopting advanced irrigation technologies, and improving soil and crop management practices, farmers can optimize water use efficiency and sustain cotton yields. Future research and policy interventions should focus on promoting climate-resilient irrigation systems to ensure the long-term sustainability of cotton farming in water-scarce regions.

5. Conclusions

The findings presented in this chapter highlight the critical importance of adaptive irrigation strategies in ensuring the sustainability of cotton production in the face of climate change and water scarcity. As global temperatures continue to rise and precipitation patterns become increasingly unpredictable, the efficient use of water resources through deficit irrigation, precision agriculture, and advanced irrigation technologies will be vital for maintaining cotton yields and water productivity.

Deficit irrigation has emerged as a viable strategy for improving water use efficiency without significantly compromising yield, provided that it is applied strategically at specific growth stages. Studies have demonstrated that maintaining irrigation at 80–90% of full irrigation can optimize yield retention while significantly reducing water consumption. The use of subsurface drip irrigation, plastic mulching, and soil moisture monitoring tools further enhances the effectiveness of deficit irrigation, ensuring that water is utilized efficiently while minimizing losses due to evaporation and runoff.

Technological advancements in irrigation management, such as remote sensing, automated irrigation systems, and decision support models, have revolutionized the way water is applied in cotton fields. The integration of these technologies allows for real-time monitoring of soil moisture and crop water stress, enabling farmers to optimize irrigation scheduling and reduce unnecessary water use. The adoption of precision irrigation techniques, including variable rate irrigation and satellite-based scheduling, has the potential to further improve water use efficiency and mitigate the impact of climate change on cotton production.

Beyond irrigation techniques, soil and crop management practices play a crucial role in improving water retention and enhancing cotton's resilience to water stress. Conservation tillage, organic amendments, and the development of drought-resistant cotton varieties contribute to more sustainable production systems. Additionally, the implementation of cover cropping and intercropping strategies can reduce soil evaporation, further conserving water resources and enhancing soil health.

Despite the progress in sustainable irrigation management, challenges remain in the widespread adoption of these practices. Economic constraints, lack of access to modern irrigation infrastructure, and limited awareness among farmers hinder the implementation of water-saving strategies. Therefore, policy interventions are necessary to support the transition to more sustainable irrigation systems. Investments in water-efficient irrigation infrastructure, financial incentives for adopting precision irrigation technologies, and the promotion of climate-resilient agricultural policies will be crucial in driving change at both the local and global levels.

In conclusion, the future of cotton production depends on the ability to adapt to the realities of climate change and water scarcity. By integrating advanced irrigation strategies, leveraging technological innovations, and adopting sustainable soil and crop management practices, cotton farmers can achieve a balance between water conservation and productivity. Continued research, policy support, and collaboration between stakeholders will be essential in ensuring the long-term sustainability of irrigated cotton farming in a rapidly changing climate.

5.References

Adeleke, A. A. (2024). Technological advancements in cotton agronomy: A review and prospects. Technology in Agronomy, 4(e008). https://doi.org/10.48130/tia-0024-0005

Ahmed, Z., Gui, D., Ali, S., Chen, X., & Qi, Z. (2022). Assessing irrigation strategies for sustainable cotton production in arid regions. International Journal of Plant Production, 18, 102–118. https://doi.org/10.1007/s42106-023-00341-5

Ahmed, Z., Gui, D., Ali, S., Chen, X., & Qi, Z. (2023). Assessing irrigation strategies for sustainable cotton production in arid regions. International Journal of Plant Production, 18, 102–118. https://doi.org/10.1007/s42106-023-00341-5

Cheng, M., Wang, H., Fan, J., Zhang, S., Wang, Y., Li, Y., Sun, X., Yang, L., & Zhang, F. (2021). Water productivity and seed cotton yield in response to deficit irrigation: A global meta-analysis. Agricultural Water Management, 255, 107027. https://doi.org/10.1016/j.agwat.2021.107027

Du, Y., Fu, Q., Ai, P., Ma, Y., & Pan, Y. (2024). Modeling comprehensive deficit irrigation strategies for drip-irrigated cotton using AquaCrop. Agriculture, 14(1269). https://doi.org/10.3390/agriculture14081269

Farooq, M., Rehman, A., Hussain, M., & Ul-Allah, S. (2021). Fiber yield and quality in cotton under drought: Effects and management. Agricultural Water Management, 255, 106994. https://doi.org/10.1016/j.agwat.2021.106994

Gui, D., Li, X., & Chen, Z. (2023). Climate change effects on cotton production in arid regions: A review of adaptation strategies. International Journal of Plant Production, 19, 88–105. https://doi.org/10.1007/s42106-023-00365-7

Hussain, S., Ahmad, A., Wajid, A., Khaliq, T., Hussain, N., Mubeen, M., Farid, H.U., Imran, M., Hammad, H.M., Awais, M., Ali, A., 2020. Irrigation scheduling for cotton cultivation. Cotton Production and Uses. Springer, Singapore, pp. 59–80.

Jans, Y., von Bloh, W., Schaphoff, S., & Müller, C. (2021). A meta-analysis of the possible impact of climate change on global cotton yield based on crop simulation approaches. Agricultural Systems, 193, 103221. https://doi.org/10.1016/j.agsy.2021.103221

Li, N., Yao, N., Chen, J., Liu, D., Biswas, A., & Wang, T. (2021). A meta-analysis of the possible impact of climate change on global cotton yield based on crop simulation approaches. Agricultural Systems, 193, 103221. https://doi.org/10.1016/j.agsy.2021.103221

Lin, M., Wang, L., Lv, G., Gao, C., Zhao, Y., Li, X., He, L., & Sun, W. (2024). Deficit irrigation effects on cotton growth cycle and preliminary optimization of irrigation strategies in arid environment. Plants, 13(1403). https://doi.org/10.3390/plants13101403

Rahman, R., Gui, D., Li, X., & Chen, Z. (2018). Evaluating Climate Change Impacts on Cotton Phenology and Yield Under Full and Deficit Irrigation Conditions in an Extremely Arid Oasis. International Journal of Plant Production, 17(49–63). https://doi.org/10.1007/s42106-022-00226-z

Rehman, A., Farooq, M., Hussain, M., & Ul-Allah, S. (2019). Drought stress and cotton production: Physiological impacts and strategies for improvement. Agricultural Water Management, 230, 105929. https://doi.org/10.1016/j.agwat.2019.105929

Schaphoff, S., Jans, Y., von Bloh, W., & Müller, C. (2018). Global cotton production under climate change – Implications for yield and water consumption. Hydrology and Earth System Sciences, 25, 2027–2044. https://doi.org/10.5194/hess-25-2027-2021

Shikha, A., Dimri, A. P., Singh, K. K., Maharana, P., & Mina, U. (2022). Risk assessment and adaptation strategies for irrigated and rainfed cotton crop production under climate change. Journal of Earth System Science, 131, 267. https://doi.org/10.1007/s12040-022-01995-x

Shukr, H. H., Pembleton, K. G., Zull, A. F., & Cockfield, G. J. (2021). Impacts of deficit irrigation strategy on water use efficiency and yield in cotton under different irrigation systems. Agronomy, 11(231). https://doi.org/10.3390/agronomy11020231

Wang, H., Yin, Z., Zhang, L., Zhao, F., Huang, W., Wang, X., & Gao, Y. (2022). Irrigation modulates the effect of increasing temperatures under climate change on cotton production of drip irrigation under plastic film mulching in southern Xinjiang. Frontiers in Plant Science, 13, 1069190. https://doi.org/10.3389/fpls.2022.1069190

Wu, F., Tang, Q., Cui, J., Tian, L., Guo, R., Wang, L., Zheng, Z., Zhang, N., Zhang, Y., & Lin, T. (2024). Deficit irrigation combined with a high planting density optimizes root and soil water–nitrogen distribution to enhance cotton productivity in arid regions. Field Crops Research. https://doi.org/10.1016/j.fcr.2024.109524

Xu, Q., Dong, X., Huang, W., Li, Z., Huang, T., Song, Z., Yang, Y., & Chen, J. (2024). Evaluating the effect of deficit irrigation on yield and water use efficiency of drip irrigation cotton under film in Xinjiang based on meta-analysis. Plants, 13(640). https://doi.org/10.3390/plants13050640

Zhang, D., Luo, Z., Liu, S., Li, W., Tang, W., & Dong, H. (2016). Effects of deficit irrigation and plant density on the growth, yield and fiber quality of irrigated cotton. Field Crops Research, 197, 1-9. https://doi.org/10.1016/j.fcr.2016.06.003

Zhangjin, R. K. S., Sajid, U. S., Badr, A., Irfan, A. S., Mehmood, L., Jhaman, D. S., Alina, S., Nasir, A. J., Sajid, F., Abdul, S. S., Tawaf, A. S., & Bhagat, K. R. (2025). Responses of cotton yield and water productivity to irrigation management: Assessment of economic costs, interactive effects of deficit irrigation water and soil types. Discover Life, 55(1). https://doi.org/10.1007/s11084-024-09677-y

Chapter 3

DETERMINATION OF CHROMOSOME DOUBLING EFFICIENCY OF TRIFLURALIN AND APM IN STEVIA

Ummu SEYITALIOGLU[1], Nesrin ORCEN[2]

1 Biotechnology Department, Graduate School of Natural and Applied Sciences, Ege University, Bornova, Izmir, 35100, Turkey, useyitalioglu@gmail.com
2 Department of Field Crops, Faculty of Agriculture, Ege University, Bornova, Izmir, 35100, Turkey

Introduction

Stevia rebaudiana (Bertoni) is a perennial, herbaceous plant belonging to the Asteraceae family, has a chromosome number of 2n=22, and is an important short-day plant due to the sweetening compounds it contains. Stevia climatic conditions are subtropical regions with an average temperature of 25°C, semi-humidity, and precipitation between 1500-1800 mm per year (Yadav 2011, Maheshwer 2005). It naturally grows at an altitude of 200-500 m (Singh and Rao, 2005). Stevia originated in the mountainous regions in the northeastern part of Paraguay (on the border with Brazil) in South America. The local people here have been using stevia for centuries in food and medicine.

Stevia is a valuable natural sweetener, 300 times sweeter than sucrose thanks to its diterpene glycoside contents and it has zero calorie. (Yao et al., 1999). Stevia is alternative to the synthetic sweeteners that are now available to the diet conscious consumers. Stevia is safe for people because the sweet compounds pass through the digestive process without chemically breaking down and so, blood sugar level can be controlled (Strauss 1995).

Eight types of diterpene glycosides were identified in stevia leaves. There are 4 important sweeteners in these glycosides. These are stevioside, rebaudioside A, rebaudioside C, and dulkoside A, which are 210, 242, and 30 times sweeter than sucrose, respectively. Rebaudioside A, which is produced in the leaves and stems of stevia, is one of the most interesting glycosides. The reason for this is that steviosides leave a bitter after taste and rebaudioside A does not leave such an aftertaste. Rebaudioside A has significant potential to be used as an alternative to other synthetic sweeteners as a substitute for sucrose (about 300 times more sweetener) (Rondi, 1980). Stevia leaves can be directly added to the beverages or could be added that is in the powder form. A liquid form of stevia is also available that could be added in the beverages. In addition to being naturally obtained and reliable, another important advantage of stevia over other artificial sweeteners is that it offers the opportunity to be boiled in the food field and used in foods cooked at high temperatures due to its high structure and pH stability (İnanç and Çınar, 2009).

In addition to its sweetening feature, stevia also has medicinal value and usage. These include antihyperglycemic, anticarcinogenic, antibacterial, antifungal and antiallergic properties (Jeppensen 2002, 2003; Rajas and Miranda, 2002; Chan et al., 1998). In addition to this, it also has a birth control feature and a preventive feature against tooth decay (Melis, 1999; Lemus-Mondaca, 2012).

As a result of studies on stevia and human health, the American Food and Drug Administration (US FDA) decided in 2008 that rebaudioside should be generally recognized as safe (Herranz-Lopez et al., 2011). The global stevia market reached a value of US$ 590 Million in 2020. Looking forward, IMARC Group expects the market to grow at a CAGR of 8.6% during 2021-2026. Despite the potential market size of stevia, agricultural production of this crop still problematic and insufficient to meet growing global demand. Research and initiatives on the production and breeding of stevia are still quite limited.

Countries studying on stevia such as Japan, China, Korea, Taiwan and Russia have achieved successful results from breeding programs and have developed new varieties with improved glycoside content and high yields. Some high-yielding varieties of Stevia are self-infertile and can only be produced vegetatively. This limits their commercial use. The success of stevia breeding depends on selection of parents, crossbreeding, establishment of adequate populations and further repeated selection. It is useful to use more than one method for the development of quantitative characters, especially in genetically heterogeneous and foreign pollinated species such as stevia. The main methods used in stevia breeding are selection breeding, repetitive selection, synthetic breeding, mutation breeding and polyploid breeding.

Polyploids are organisms that have more than one set of chromosomes on diploid chromosomes (Acquaah 2007; Chen 2010; Comai 2005; Ramsey and Schemske 1998). Obtaining polyploidy is a widely used technique for agronomic yield in economically important plants. With polyploidy, individuals can adapt better with increasing organ and cell sizes (Allard 1960; Guerra 1988; Carputo et al., 2006; Sattler et al., 2016). It is possible that tetraploid plants could potentially be used with greater leaf size, depth, increased mass and yield than diploid ratios. In addition, via polyploidy, secondary metabolites increase qualitatively and quantitatively in industrially significant plants such as stevia (Dhawan and Lavania 1996). Polyploid plant is obtained with the use of chemicals known as antimitotic agents. Colchicine is the most common, oldest chemical used in chromosome folding, first reported as an antimitotic in the 1930s (Blakesslee and Avery 1937). Colchicine's chromosome folding takes place by holding onto microtubules and protecting the spindle fibers. Colchicine shows that mammalian tubulins are more abundant than plant tubulins (Hansen et al., 2000). Therefore, colchicine is more mutagenic in mammals than in plants (Bürün 1988). Recently, as an alternative to colchicine, herbicides with less mutagenic antimicrobial effect have come to power (Trifluralin, Amiprofos-methyl (APM), oryzalin et al.). These herbicides can be effective even at lower levels of colchicine. They are also more economical and less toxic than colchicine (Hansen et al., 2000). In addition to all these, less mixploid and chimeric plants were observed in polyploid plants obtained with other herbicides compared to colchicine (Zlesak et al., 2005).

Colchicine has been used in all of the polyploid stevia studies reported so far. In this research, the success of obtaining polyploid stevia by using trifluralin and APM was analyzed and the agronomic and cytological properties of the obtained plants were investigated.

Materials and methods

Plant materials

In June 2022, Stevia (*Stevia rebaudiana* Bertoni) plants originated from Paraguay (clonal propagated), from the Neworganik manufacturer were provided. Apical meristems of one month old seedlings were exposed to antimitotic agents as explants. For each application factor, 5 Stevia seedlings were used.

Methods

In this study, Trifluralin and Amiprofos methyl (APM) were used as antimitotic agents to obtain polyploid stevia from diploid stevia plants. The antimitotic agent used, doses and times are given in Table 1. In vivo application of antimitotic agents was carried out by optimization in the study of Jeff R. Jones et al. in 2008.

Application No	Antimitotic Agent/ Dose / Time	Application No	Antimitotic Agent/ Dose / Time
T0	Control	A0	Control
T1	Trifluralin 10 µM/24 hours	A1	APM 15 µM/24 hours
T2	Trifluralin 10 µM/48 hours	A2	APM 15 µM/48 hours
T3	Trifluralin 10 µM/72 hours	A3	APM 15 µM/72 hours
T4	Trifluralin 30 µM/24 hours	A4	APM 25 µM/24 hours
T5	Trifluralin 30 µM/48 hours	A5	APM 25 µM/48 hours
T6	Trifluralin 30 µM/72 hours	A6	APM 25 µM/72 hours
T7	Trifluralin 50 µM/24 hours	A7	APM 40 µM/24 hours
T8	Trifluralin 50 µM/48 hours	A8	APM 40 µM/48 hours
T9	Trifluralin 50 µM/72 hours	A9	APM 40 µM/72 hours

Table 1. *Chemicals used in in vivo antimitotic agent applications, dosages and exposure times.*

For control, warm agar suspended with distilled water was dripped onto the apical meristems of stevia seedlings instead of antimitotic chemicals. All the treatments applied to the other plants were also applied to the control plants. For APM application, 5.5g/L agar and APM solutions were suspended at 50 °C for each dose. For each application, one drop (0.5 ml) of warm (~40 ^{0}C) APM suspension was placed in the apical meristem of the seedlings with a pipette in the early morning. In order not to prevent the effect of the antimitotic agent by evaporation, the pots of the treated stevia seedlings were covered with polyethylene bags. Semi-solid antimitotic agent suspension was renewed after 24 hours in 48 and 72 hour applications. Trifluralin applications were performed just like APM application.

Stevia seedlings treated with antimitotic agents were placed in 30 cm pots containing moist soil with a pH of 6.7 to 7.2, receiving plenty of light. Irrigation was performed twice a week and fertilization was carried out at regular intervals.

Morphological Analysis

Plant Height Measurement

In a period close to harvest maturity, the height from the soil surface to the tip of the plant of 5 selected plants for each application was measured in meters and averaged.

Leaf Length and Width Measurement

At the beginning of flowering, leaf length and width were calculated by taking the mean measurements from the lower, middle and upper leaves of 5 randomly selected plants for each application.

Fresh Leaf Weight Per Plant (g/plant)

Fresh leaf weights per plant were determined by weighing 5 randomly selected plants from each application.

Dry Leaf Weight Per Plant (g/plant)

After each application, the harvested samples were dried in an oven at 40 °C for 72 hours, and the dry leaf weights per plant were determined by weighing.

Cytological Analysis

Chromosome Count and Ploidy Determination

In order to determine the ploidy status of the plants obtained in the applications, chromosome counts were carried out with the method given by Örçen N. (2006) with reference to Walter (1961). According to this method, the light green core leaves of the plants or the corollas of very small (2-4 mm) flower buds were taken early in the morning and left in 8-hydroxyquinoline (0.002 mol/l) for 3.5 hours at 18-20°C. Then, it was washed 5-6 times with tap water, the excess water was removed with blotting paper, and it was treated in a 1:2 ratio of HCL + 96% ethyl alcohol for 6 minutes. Then it was washed again with tap water 8-10 times and taken into pure water. After thoroughly dewatering with blotting paper, a piece in the size of a pinhead from the bottom of the leaf and both sides of the midrib and the same size from any part of the corolla was taken and 2% aceto-orsein was dripped on it and crushed preparations were prepared. Chromosome numbers and ploidy levels were determined by examining the prepared preparations under a light microscope.

Examination of the Number and Size of Stoma Cells

Stoma cell number and size is one of the common methods used to determine ploidy levels. In order to determine the ploidy level of the treated plants, the lower epidermis of the leaf was scraped with a forceps to determine the number and length of stomata, and the preparation was prepared with water. The number and size of stomatal cells in approximately 20 cells were measured with an ocular micrometer and the averages were taken, and the values were used to determine the ploidy level.

Investigation of Pollen Size

The size of pollen dust is also an important indicator in ploidy control (Blakeslee and Avery, 1937). For this reason, in this study, the diameters of the swollen pollen were measured under the light microscope by preparing a preparation with aceto-orsein to determine the pollen sizes (Örçen N., 2006). For this, a drop of 1% aceto-orsein was dripped onto the slide, pollen taken from the anthers of the flower bud that was about to open was placed on it and covered with a lamella. Thus, the average pollen size was determined by measuring 20 pollen diameters for each plant with an ocular micrometer in the prepared preparations.

Data Analysis

Trifluralin and APM antimitotic agent applications were statistically analyzed according to the randomized block split plot design. Antimitotic agent was designed as the main plot, dose and durations as subplots. The effects of dose, time and dose x time interaction factors on polyploidy in Trifluralin and APM applications and the statistical differences between morphological and cytological features in the applied plants were determined by ANOVA test. For those with significant differences at $p<0.05$ level between the means, Duncan multiple comparison tests were applied and different groups were identified and groupings were made.

Results and Discussion

According to the ANOVA results, different antimitotic agents and their different concentrations showed a significant difference ($p<0.05$) for polyploid stevia induction. The mean polyploidization rate in trifluralin treatment was reported as 33.33%. The highest polyploidization rate in the plants treated with trifluralin was obtained at a concentration of 50 µM during the 24-hour treatment period. This was followed by T1, T3, T4, T5, T6 and T9 applications which showed 40% polyploidization. The highest tetraploidization rate was obtained at 10 µM trifluralin concentration for 24 hours (T1 application), the second highest tetraploidization rate was obtained at T7, T6 and T4 applications. The lowest polyploidization rate was observed in 10 µM concentration for 48 hours (T2) and 50 µM concentration for 48 hours (T8) applications. The average polyploidization rate in APM application was determined as 22.22%. The highest polyploidization rate in APM applied plants was observed in A9, A8, A7 and A5 applications. The highest tetraploidization rate in APM-treated plants was obtained at APM 40 µM concentration in the 24 hour treatment period (A7), the second highest tetraploidization rate at APM 40 µM concentration in the 48-hour treatment period (A8) and thirdly in the 24 hour treatment period at APM 25 µM concentration(A4). The lowest polyploidization rate in APM application was observed at 15 µM concentration of APM in 24-hours (A1), 48-hours (A2) and 72-hours (A3) applications.

When the polyploidy activity of trifluralin and APM antimitotic agents on Stevia was compared, it was determined that trifluralin was more effective than APM. In addition, in terms of morphological character analysis, more stable results were observed in plants treated with trifluralin. Fluctuations were observed as a result of APM applications, especially for fresh and dry leaf weight traits per plant. The polyploidization rate of trifluralin and APM applications is given in Figure 1.

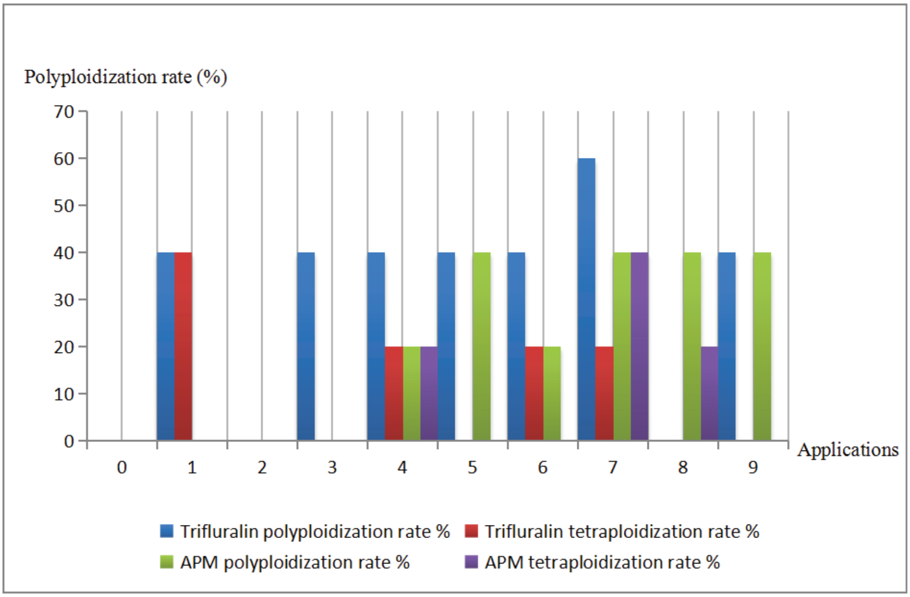

Figure 1. *Polyploidization rate of S. rebaudiana after trifluralin and APM applications.*

ANOVA results showed that diploid and polyploid plants have significantly differences for morphological and cytological characters. Variance analysis of morphological and cytological characters of diploid, tetraploid and mixoploid plants are given in detail in Table 2 and 3.

	Plant Height (cm)	Leaf Lenght (cm)	Leaf Width (cm)	Fresh Leaf Weigt (gr)	Dry Leaf Weight (gr)
Control (Diploid)	50,6±9,07b	3,87±0,19b	2,29±0,19	75,97±7,44b	33,35±4,52b
Tetraploid	64,28±14,15a	4,85±1,11ba	2,45±0,71	130,45±25,91a	60,27±13,35a
Mixoploid	67,51±12,01a	5,75±1,39a	2,81±0,82	113,42±38,76a	52,63±19,27a
Sum of Squares	1093,03	14,90	1,37	8863,05	2195,25
Degrees of Freedom	2,00	2,00	2,00	2,00	2,00
Mean Squares	546,52	7,45	0,69	2460,34	624,82
Test Statistics (F)	**3,602***	**5,145****	1,30 ^{ns}	**4,285***	**4,223***
P	0,041	0,013	0,288	0,026	0,027

(n=9, n represents the within group number of each group with different ploidy levels)

*: 0,05 significantly different, **: 0,01 significantly different, ns: it is not significantly different

Different letters indicate significant differences detected (p<0,05).

Table 2. *Values of Morphological Characters and Variance Analysis Results in Diploid and Polyploid Plants*

According to the results of variance analysis of morphological characters, significant differences were found at the 0.05 level for plant height, fresh leaf weight per plant, dry leaf weight per plant characters and at the 0.01 level for leaf length character among tetraploid, mixoploid and diploid control plants. No significant difference was observed among tetraploid, mixoploid and diploid control plants in terms of leaf width characters.

	Stoma Lenght (µm)	**Stoma Width (µm)**	**Stoma Number (Unit/mm²)**	**Pollen Diameter (µm)**
Control (Diploid)	25,75±0,01b	20,60±0,01b	8,00±1,00a	18,54±1,24c
Tetraploid	32,47±7,19a	38,82±4,72a	3,67±0,50b	27,65±1,12a
Mixoploid	28,06±3,96ba	37,58±8,52a	6,38±0,89c	23,24±2,05b
Sum of Squares	174,30	1268,37	70,42	276,78
Degree of Freedom	2,00	2,00	2,00	2,00
Mean Squares	87,15	634,18	35,21	138,39
Test Statistics (F)	**3,58***	**13,79****	**53,56****	**47,06****
P	0,042	<0,001	<0,001	<0,001

(n=9, n represents the within group number of each groupwith different ploidy levels)

*: 0,05 significantly different, **: 0,01 significantly different

Different letters indicate significant differences detected (p<0,05).

Table 3. *Values of Cytological Characters and Variance Analysis Results in Diploid and Polyploid Plants*

According to the variance analysis results of cytological characters, a significant difference was found at the 0.05 level among tetraploid, mixoploid and diploid control plants for stomata length character. A significant difference at the 0.01 level was determined between tetraploids, mixoploids and diploids for all stomata number, stomata width and pollen diameter characters.

In general, polyploid plants show characteristic tissue or organ enlargement (gigant effect) compared to diploid plants, and the development and growth of plants are strongly tolerant to biotic and abiotic stresses (Sun et al., 2004). Confirming this information, in this study, tetraploid plants showed an increase in plant height, leaf length, fresh and dry leaf weight per plant compared to control plants and a significant difference was found between them at p<0.05 level as a result of variance analysis. Although tetraploid plants showed an increase in leaf width compared to diploid control plants, this increase was not found to be significant at p<0.05 level as a result of variance analysis.

The significant increase in fresh and dry leaf weight of polyploid Stevia plants obtained as a result of the study indicates that Stevia glycosides, which are directly proportional to the amount of fresh and dry leaves, also increase significantly in these polyploid plants.

Morphological Analysis

Plant Height (cm) *Measurement*

It was observed that the plants treated with antimitotic agents were taller than the control plants. According to the variance analysis of plant height characteristics as a result of trifluralin and APM applications, a statistically significant difference was determined at $p<0.05$ level for the dose factor and dose x time interaction factor. However, it was determined that there was no statistically significant difference on the plant height character of the time factor. Duncan multiple comparison test was performed for dose and dose x time interaction factors.

The highest plant height was determined as 79±21.3 cm and 72.9±12.0 cm in 50 µM/72 hours (T9), 50µM/24 hours (T7) applications, respectively. The lowest plant height was found in T6 application with 53.9±8.5 cm. As a result of APM applications, the highest increase in plant height was detected in the 15 µM/72 hours (A3) (96±1.4 cm) application. The lowest increase was seen in the 15 µm/48 hours (A2) (53.3±1.8 cm) application.

Leaf Length and Width (cm) *Measurement*

It was observed that the leaf lengths and widths of the plants treated with antimitotic agents were generally longer than the control plants. As a result of variance analysis of leaf length measurements of trifluralin applications, significant differences were found at $p<0.05$ level for the time factor and $p<0.01$ level for the dose x time interaction factor. No significant difference was found for the dose factor. The highest difference was seen in the 50 µm/24 hours (T7) application (7.0±0.8 cm). The lowest leaf length was observed in the 30 µm/72 hours (T6) application with 3.8±0.8 cm.

When variance analysis was performed on leaf length characters as a result of APM applications, a significant difference was determined at $p<0.05$ level for the dose factor, and at 0.01 level for the time and dose x time interaction factors. Compared to control plants, the highest average leaf length was determined as 6.2±0.3 cm in the 25 µm/72 hours (A6) application. The lowest average leaf length was recorded as 4.2±0.3 cm in the 25 µm/24 hours (A4) application.

As a result of variance analysis of leaf width measurements of trifluralin applications, a statistically significant difference was found at $p<0.01$ level for the time factor and dose x time interaction factor. No statistically significant difference was found for the dose factor. The highest leaf width

(4.0±0.2 cm) was achieved in 50 µm/24 h (T7) application. The lowest leaf width (1.7±0.5 cm) was recorded in 30 µm/72 h (T6) application.

As a result of variance analysis of the mean leaf width values of Stevia plants to which APM applications were made, no statistically significant difference was observed in the dose and time factors. A significant difference was observed at the level of $p<0.01$ for the dose x time interaction factor. The highest leaf width was found to be 3.1±0.2 cm in the 25 µm/72 hours (A6) application. The lowest leaf width was determined to be 1.9±0.8 cm in the 40 µm/48 hours (A8) application.

Fresh Leaf Weight Per Plant (g/plant)

Compared to control plants, an increase in fresh leaf weight per plant was observed in all applications of trifluralin. As a result of variance analysis, a significant difference was observed between the control and applications at $p<0.01$ level for all dose, time and dose x time interaction factors. Duncan multiple comparison test was performed to group the differences. The highest fresh leaf weight per plant was determined as 145.8±20.7 g in the 10 µm/72 hours (T3) application, and the lowest fresh leaf weight per plant was determined as 78.1±28.8 g in the 30 µm/24 hours (T4) application.

Compared to control plants, a significant increase was observed in terms of fresh leaf weight per plant in some applications of APM (A2, A3, A4, A5, A6, A8), no significant difference was observed in some (A7). On the other hand, some factors of APM application (A1, A9) showed a decrease in fresh leaf weight per plant. According to the variance analysis result, there is no significant difference at $p<0.05$ level for dose and time factors. A significant difference was observed at $p<0.01$ level for dose x time interaction factor. The highest fresh leaf weight per plant was recorded as 170.1±88.9 g in 15 µm/72 h (A3) application. The lowest fresh leaf weight per plant was determined as 47.0±19.0 g in 15 µm/24 h (A1) application. It is thought that the decrease in fresh leaf weight per plant as a result of some APM applications is due to the possibility of the chemical having a toxic effect.

Dry Leaf Weight Per Plant (g/plant)

Average dry leaf weight values per plant are directly proportional to fresh leaf weight values per plant. In general, it has been reported that the application of trifluralin caused a greater increase in dry leaf weight per plant than the application of APM.

A general increase in dry leaf weight per plant was observed in trifluralin applications compared to control plants. As a result of variance analysis, a significant difference was found at the level of $p<0.05$ for the dose factor and at the level of 0.01 for the time and dose x time interaction factors. The highest dry leaf weight per plant was determined as 68.0±11.6 g in 10 µm/72 h (T3) application. The lowest dry leaf weight per plant was determined as 34.2±15.0 g in 30 µm/24 h (T4) application.

It was observed that there was a fluctuation in dry leaf weight values in APM application. While some APM applications showed a decrease in dry leaf weight per plant, some of them were equivalent to control plants and some increased compared to control plants. According to the variance analysis, no statistically significant difference was found at the $p<0.05$ level for the dose and time factors. A significant difference was found at the 0.01 level for the dose x time interaction factor. The highest dry leaf weight per plant was determined as 79.8±43.8 g in 15 µm/72 h (A3) application. The lowest dry leaf weight per plant was determined as 20.7±.8.9 g in 15 µm/24 h (A1) application.

Cytological Analysis

Chromosome Count and Ploidy Determination

According to the analyzes of chromosome count and ploidy level determination, 5 tetraploid and 10 mixoploid stevia plants were determined as a result of Trifluralin applications. It has been observed that the most appropriate dose and duration of Trifluralin treatments are Trifluralin 10 µM/24 hours and Trifluralin 50 µM/24 hours, respectively. As a result of APM applications, 4 tetraploid and 6 mixoploid stevia plants were identified. In APM applications, the most appropriate dose and time for obtaining tetraploid stevia was determined as APM 40 µM/24 hours.

It was observed that mixoploidy increased in the plants obtained as the dose and duration increased in trifluralin and APM applications. In addition, fewer mixoploid plants were observed as a result of APM applications compared to trifluralin applications.

Examination of the Number (Unit/mm^2) and Size of Stoma Cells (µm)

Compared to diploid plants, the width and length of guard cells and leaf stomatal area of polyploid plants increase, but the number of stoma per unit area decreases. This situation is used as a simple and effective parameter to distinguish ploidy (Tao et al., 2014; Robinson et al., 2018; Yuan et al., 2009).

The average stomatal cell sizes were determined as a result of the examinations and counts made around 20 cells in stevia plants exposed to antimitotic agents applications. According to these analyses, 9 polyploid stevia plants were identified in trifluralin applications.

The highest polyploid plant production was observed in Trifluralin 50 µM/24 h (T7) (2 units), 30 µM/72 h (T6) (2 units) and 10 µM/24 h (T1) (2 units) applications. This was followed by T3 (1 unit), T4 (1 unit) and T9 (1 unit) applications.

As a result of trifluralin applications, a decrease was observed in the mean stoma count values for all dose, time, and dose x time interaction factors. According to the variance analysis, a significant difference was found at the level of $p<0.05$ for the dose factor. No statistically significant difference was found for the time and dose x time interaction factors. The lowest average stomata number was determined as 5.7±1.6 in the 10 µM application. The highest average stomata number was determined as 7.3±0.9 in the 30 µM application.

In trifluralin applications, the average stoma width values were found at the same level as the control group in T1, T4 and T8 applications. Other applications showed an increase in the average stoma width compared to the control group. According to the stoma width variance analysis result, no statistically significant difference was observed between the treatments and control groups for the dose factor, time factor and dose x time interaction factor.

The stoma length values for trifluralin applications increased compared to the control group. According to the variance analysis, a significant difference was found at the level of $p<0.05$ for the dose factor and $p<0.01$ for the dose x time interaction factor. The highest stoma length was determined as 44.6±4.7 µm in the 30 µm/48 hours (T5) application. The lowest stoma length was recorded as 27.6±4.7 µm in the 30 µm/72 hours (T6) application.

In APM applications, 8 polyploid plants were defined. The highest polyploid plant yield was seen in 40 µM/24 hours (A7) (2 units) and 40 µM/48 hours (A8) (2 units) applications. This was followed by A4 (1 unit), A5 (1 unit), A6 (1 unit) and A9 (1 unit) applications.

As a result of APM applications, a decrease was observed in the stoma number values for all dose, time, and dose x time interaction factors. According to the variance analysis, no statistically significant differences were observed between the treatment and control groups for dose, duration and dose x time interaction factors.

According to the stoma width variance analysis in APM applications, no statistically significant difference was observed for the dose and time factors. A significant difference was detected for the dose x time interaction factor at the level of $p<0.05$. The highest stoma width was determined as 36.6±4.3 µm in the 25 µm/72 hours (A6) application. The lowest stoma width was determined as 25.8±0.0 µm in the A1 and A2 applications in the same group as the control group.

When the stoma length character was examined as a result of APM applications, an increase was detected compared to the control group. According to the variance analysis, a significant difference was found at the level of $p<0.01$ for the dose factor, and at the level of $p<0.05$ for the time and dose x time interaction factors. The highest stoma length was found to be 38.4±5.6 µm in the 25 µM/48 hours (A5) application. The lowest increase in stoma length was found to be 25.3±5.5 µm in the 15 µm/24 hours (A1) application.

Investigation of Pollen Size (µm)

While the pollen sizes were between 17.72 µm and 20.6 µm among the control plants, the pollen sizes of the plants obtained as a result of trifluralin applications were between 17.6 µm and 28.2 µm. The pollen sizes of the plants obtained as a result of APM applications are between 17.4 µm and 28.1 µm. In addition, it was determined that the pollen sizes were directly proportional to the stoma sizes.

According to the variance analysis for trifluralin applications, a significant difference was found for the dose factor at the level of $p<0.05$. No statistically significant difference was found for the time and dose x time interaction factors. The highest increase in pollen diameter was observed in the 10 µM application (22.6±3.7 µm). The lowest increase in pollen diameter was recorded in the 30 µM application (19.3±1.5 µm).

According to the variance analysis of APM applications, a significant difference was observed at the level of $p<0.05$ for the dose factor, similar to the application of trifluralin. No statistically significant difference was observed for the time and dose x time interaction factors. The highest pollen diameter was observed in the 40 µM application (22.3±4.2 µm). The lowest pollen diameter was determined in the 15 µM application (18.7±0.8 µm).

It was observed that tetraploid plants obtained as a result of antimitotic agent applications formed several flower clusters. Pollen size and vitality were also observed by staining with aceto-orcein and examining under a microscope. It is estimated that the pollens have low vitality due to their pale color. Similar results were also found in the study of Yadav et al. (2013). This is expected since the normal tetrad formation percentage is low in tetraploid plants.

Conclusions

In this study, different antimitotic agents other than colchicine were used for the first time to obtain polyploid plants in Stevia. For this purpose, trifluralin and APM antimitotic agent applications to diploid Stevia plants were carried out in vivo at different doses and durations. As a result of both antimitotic agent applications, tetraploid and mixoploid Stevia plants were obtained. Trifluralin and APM acted as antimitotic and made chromosome folding in stevia seedlings. According to the studies on polyploid stevia obtained so far, a high rate of polyploid stevia was reported in our study.

Additionally, a method for polyploidy induction was developed in this study. It would be useful to use this method as a model for polyploidy induction in industrially important plants.

Comparing the effectiveness of trifluralin and APM antimitotic agents on obtaining polyploid Stevia, it was determined that trifluralin (33.33%) is more effective than APM (22.22%). In addition, more stable results were obtained from trifluralin applications in terms of morphological character analysis. Fluctuations (increases and decreases) were observed as a result of APM applications, especially for fresh and dry leaf weight traits per plant.

Yadav et al. (2013) and Mahdi (2012) stated that there is a significant difference between polyploid Stevia plants in terms of characteristics such as plant height, leaf length and width, leaf thickness, leaf color darkness, and that polyploid plants have darker colors and larger leaves and are taller than diploids. In general, polyploid plants show characteristic tissue or organ growth and the development and growth of plants strongly create tolerance to biotic and abiotic stresses (Sun et al., 2004). Confirming this information, in this study, tetraploid plants showed an increase in plant height, leaf length, fresh and dry leaf weight per plant compared to control plants and as a result of variance analysis, a significant difference was found between them at the level of $p<0.05$. Although tetraploid plants showed an increase in leaf width character compared to diploid control plants, as a result of variance analysis, this increase was not found to be significant at the level of $p<0.05$.

When the results were examined, it was seen that the most appropriate trifluralin dose for polyploid stevia induction was 10 and 30 µM. The

24 hour application was the most effective time without any dose discrimination. It was observed that the polyploidization rate increased as the dose rate increased in APM application. When the results were evaluated, it was determined that the most appropriate dose factor for polyploidization was 40 µM for APM. When the results were evaluated in terms of the time factor, it was determined that the 24 hour application was the most effective time without any dose discrimination. It was determined that the number of mixploid plants increased as the time factor increased regardless of antimitotic agent.

When variance analyses were examined, although dose, time and dose x time interaction factors had different effects on morphological characters, the common significant difference source for dose factor was generally evaluated as 50 µM and 10 µM in trifluralin application, 40 µM in APM application, 72 hours for time factor regardless of antimitotic agent, 50 µM/24 hours (T7) and 10 µm/72 hours (T3) in trifluralin application, 25 µm/24 hours (A4) and 25 µm/72 hours (A6) in APM application. This application evaluation can be used as an important data source for future Stevia polyploidy studies.

All polyploid stevia studies reported to date have used colchicine. This study has shown that the use of low doses of trifluralin and APM as in vivo antimitotic agents for the production of polyploid Stevia is quite effective. Preferring chemicals such as Trifluralin and APM instead of colchicine is more appropriate and is a very significant issue in terms of plant and human health and environmental safety.

When all the results were evaluated in general, successful results were obtained in terms of obtaining tetraploid stevia plant with trifluralin and APM antimitotic agents at low doses and times. However, further studies are required in order to use these results in a practical and effective way.

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References

Acquaah, G. 2007. '*Principles of plant genetics and breeding*'. UK. T.J., International Ltd.

Allard,R. W. 1960. 'Principles of plant beeding'. New York, NY. John Wiley and Sons, Inc. Sayfa 485.

Blakeslee A.F., Avery A.G. 1937. 'Methods of inducing chromosome doubling in plants: By treatment with colchicine'. *J Hered* 28: 393–411.

Bürün B, 1988. 'Androgenetik tütün haploidlerinden dihaploidlerin elde edilmesinde asenaftenden yararlanma'. Ege Üniversitesi Fen Bilimleri Enstitüsü, Doktora tezi, Bornova.

Carputo D., Camadro E. L. ve Peloquin S.J., 2006, Terminology for polyploids based on cytogenetics behavior: Consequences in genetics and breeding. Plant Breeding Reviews. 26: Chapter 4.

Chan,P.,Xu,D. Y.,Liu,J. C.,Chen,Y. J.,Tomlinson, B., Huang,W. P. and Cheng,J. T. 1998.' The effect of stevioside on blood pressure and plasma catecholamines in spontaneously hypertensive rats'. Life Sci. 63: 1679-1684.

Chen Z. 2010. 'Molecular mechanisms of polyploidy and hybrid vigor'. Trends in plant science 15:57-71.

Comai L. 2005. 'The advantages and disadvantages of being polyploid'. *Nat Rev Genet* 6: 836–846.

Guerra,M. 1988. 'Introduc¸a˜o a` Citogene´tica Vegetal. Editora Guanabara. Rio de Janeiro'. 142 pp. [English summary]

Hansen A.L., Gertz A., Joersbo M., Andersen S.B. 2000. 'Chromosome doubling in vitro with amiprophosmethyl in *Beta vulgaris* ovule culture'. Acta Agrıculturae Scandınavıca Sectıon B-Soıl and Plant Scıence 50 (2): 89-95.

Hansen A.L., Gertz A., Joersbo M., Andersen S.B. 1998. 'Antimicrotubule herbicides for *ın vitro* chromosome doubling in *Beta vulgaris* L. ovule culture'. Euphytica 101:231-237.

Herranz, Lopez, M., Barrajon, Catalan, E., Beltran Debon, R., Joven, J. and Micol, V. 2011. 'Potential medicinal benefits of high intensity sweetener from Stevia'. Int. Sugar J., 113: 792-797.

İnanç, A.L., Çınar, İ. 2009. 'Alternatif doğal tatlandırıcı: Stevya'. *Gıda,* 34(6), 411-415.

Jeppesen,P. B., Gregersen,S.,Alstrup,K. K. and Hermansen, K. 2002. 'Stevioside induces antihyperglycaemic, insulinotropic and glucagonostatic effects in vivo: studies in the diabetic Goto-Kakizaki (GK) rats'. Phytomedicine 9: 9_14.

Jeppesen,P. B.,Gregersen, S.,Rolfsen, S. E. D.,Jepsen,M., Colombo,M.,Agger,A., Xiao,J., Kruhøffer,M.,Orntoft, T. and Hermansen,K. 2003. 'Antihyperglycemic and blood pressure-reducing effects of stevioside in the diabetic gotokakizaki rat'. Metabolism 52: 372_378.

Jones, J.R. , Ranney, T.G. & Eaker, T.A. 2008. 'A novel method for inducing polyploidy in *Rhododendron* seedlings.' *J. Amer. Rhododendron Soc.* 62 130 135.

Lemus-Mondaca R., Vega-Gálvez A., Zura-Bravo L., Ah-Hen K. 2012. 'Stevia rebaudiana Bertoni, source of a high-potency natural sweetener: a comprehensive review on the biochemical, nutritional and functional aspects'. Food Chem 132:1121–1132.

Mahdi, S., 2012. Induction of genetic variability by colchicine treatment in Stevia rebaudiana Bertoni. M. Sc. Thesis, University of Agriculture Sciences (GKVK) Bangalore, Karnataka.

Maheswar H.M. 2005. 'Effect of Different Levels of Nitrogen and Dates of Planting on Growth and Yield of Stevia (*Stevia rebaudiana* Bertoni)'. Department of Horticulture College of Agriculture, Dharwad University of Agricultural Sciences, Dharwad, M.Sc. Thesis. 66 P.

Melis,M. S. 1999. 'Effects of chronic administration of Stevia rebaudiana on fertility in rats'. J. Ethnopharmacol. 67: 157_161.

Örçen N. 2006. 'Androgenetik Tütün Haploidlerinde Asenaften ve Trifluralinin Antimitotik Etkileri'. Ege Üniversitesi Fen Bilimleri Enstitüsü, Doktora tezi, Bornova.

Ramsey J, Schemske D.W. 1998. 'Pathways, mechanisms, and rates of polyploid formation in flowering plants'. *Annu Rev Ecol Syst* 29: 467–501.

Randi,A. M. 1980. 'Germinacao de Stevia rebaudiana Bert.' M.Sc. thesis. Universidade Estadual de Campinas, Campinas, Brazil. [English summary.]

Randi,A. M. 1980. 'Germinacao de Stevia rebaudiana Bert.' M.Sc. thesis. Universidade Estadual de Campinas, Campinas, Brazil. [English summary.]

Robinson, D.O., Coate, J. E., Singh, A., Hong, L., Bush, M., Doyle, J.J., Roeder, A.H.K., 2018. Ploidy and Size at Multiple Scales in the Arabidopsis Sepal. The Plant Cell. 30: 2308 –2329.

Sattler M.C., Carvalho C.R. ve Clarindo W.R. 2016. 'The polyploidy and its key roe in plant breeding'. Planta 243: 281-296.

Singh S.D., Rao G.P. 2005. 'Stevia: The herbal sugar of 21st century'. *Suger Tech* 7: 17–24.

Strauss,S. 1995. The perfect sweetener? Technol. Rev. 98: 18 20.

Sun, M.H., Zhang, S.N., 2004. Application of polyploid breeding in horticultural crops. Jiangsu Agricult. Sci. (1), 68–72.

Tao, J.F., 2014. Study on the regeneration system and polyploidy induction with identification in Rhododendronra cemosum Franch. Yunnan Agricultural University, Kunming Yunnan Province, China.

Yadav A.K., Singh S., Dhyani D., Ahuja P.S. 2011. 'A review on the improvement of stevia [*Stevia rebaudiana* (Bertoni)]'. *Can J Plant Sci* 91: 1–27.

Yadav, A.K., Sıngh, S.,Yadav, S.C., Dhyanı, D., Bhardwaj, G., Sharma, A., and Sıngh, B., 2013. Induction and morpho-chemical characterization of Stevia rebaudiana colchiploids. Indian Journal of Agricultural Sciences 83 (2): 159–65.

Yao,Y., Ban M. and Brandle,J. 1999. 'A genetic linkage map for Stevia rebaudiana'. Genome 42: 657_661.

Yuan, S.X., Liu, Y.-M., Fang, Z.Y., Yang, L.M., Zhuang, M., Zhang, Y.Y. and Sun, P.T., 2009. Study on the relationship between the ploidy level of microspore-derived plants and the number of chloroplast in stomatal guard cells in Brassica oleracea. Agric. Sci. China, 8(8):939-946.

Zlesak D.C., Thill C.A., Anderson N.O. 2005. 'Trifluralin-mediated polyploidization of *Rosa chinensis minima* (Sims) Voss seedlings'. Euphytıca 141 (3): 281-290.

Chapter 4

SUSTAINABLE FOOD SOLUTIONS IN AN URBANIZING WORLD: VERTICAL FARMING

Haydar BALCI[1]

1 Assistant Professor, Van Yüzüncü Yıl University, Gevaş Vocational School, Department of Plant and Animal Production, Van, TÜRKİYE Orcid No: 0000-0003-0210-3639 E-Mail: haydarbalci@yyu.edu.tr

Introduction

As urbanization continues to accelerate worldwide, agricultural production and food security have become critical global concerns. Traditional farming methods are increasingly insufficient to meet the food demands of a growing population, while environmental pressures such as decreasing agricultural land, water scarcity, and climate change necessitate the adoption of sustainable production models. This situation compels the development of innovative solutions that push the boundaries of conventional agriculture. In this context, vertical farming emerges as an innovative agricultural model that integrates into urban areas, maximizing productivity while minimizing land, water, and resource usage. Supported by soilless farming techniques, artificial intelligence-assisted production systems, and smart agricultural technologies, vertical farming has the potential to play a crucial role in the future of food production. This chapter explores the relationship between urbanization and vertical farming, the challenges faced by traditional agriculture, and the solutions offered by vertical farming to ensure sustainable food production in urban settings.

1. Urbanization and Agriculture: The Transition from Traditional Methods to Vertical Farming

1.1. The Emergence of Vertical Farming: The Relationship Between Agriculture and Urbanization

Since the Industrial Revolution, urbanization has accelerated globally, leading to a decline in rural populations (FAO, 2019). The increasing urban population has necessitated the integration of food production systems into urban environments. As a response, vertical farming has been developed as an alternative to traditional agriculture, particularly in urban areas, to achieve high-yield production with limited land use (Despommier, 2010, 2011).

The concept of vertical farming has evolved through various research efforts since the mid-20th century and has been further advanced with modern technologies (Specht et al., 2014). Soilless farming techniques such as hydroponics, aeroponics, and aquaponics are fundamental to enabling vertical farming. These methods significantly reduce water consumption, enhance productivity, and promote sustainable urban food production (Al-Kodmany, 2018).

1.2. The Growing Challenges of Traditional Agriculture with Urbanization

Traditional farming methods require extensive land, suitable climatic conditions, and large amounts of water. However, the rapid expansion of urban areas has led to the reduction of agricultural lands and limited the feasibility of agriculture in urban environments (FAO, 2019). Additionally, conventional farming practices contribute to environmental issues such as water depletion and soil erosion (Tilman et al., 2011).

Another significant challenge posed by urbanization is food logistics. Transporting agricultural products from rural areas to urban consumers increases the carbon footprint and creates disruptions in the supply chain (Godfray et al., 2010). Vertical farming addresses these challenges by enabling local food production within cities, thereby reducing logistical costs and ensuring local food security (Benke & Tomkins, 2017).

1.3. Vertical Farming: An Adaptable Solution for Urbanization

Vertical farming has emerged as an innovative solution to the food production challenges posed by urbanization. This system, which can be implemented indoors, in containers, or on rooftops, achieves high productivity with lower water, fertilizer, and land use than traditional agriculture (Kalantari et al., 2018). For instance, hydroponic systems allow up to 90% less water consumption compared to conventional farming (Van Delden et al., 2021).

Furthermore, urban applications of vertical farming localize food production, shorten supply chains, and minimize food waste (O'Sullivan et al., 2020). Repurposing unused urban spaces such as vacant buildings, rooftops, and containers enhances cities' food production capacity (Bayraklı & Altındisli, 2020). Moreover, vertical farming systems, supported by smart agricultural technologies, incorporate LED lighting, sensor-based control mechanisms, and artificial intelligence-driven growth optimization (Kozai, 2013, 2018).

In conclusion, vertical farming presents an adaptable and sustainable model for addressing food production challenges in urbanized environments. As these systems become more widespread, cities may evolve into self-sufficient food production centers.

2. Definition and Working Principles of Vertical Farming

2.1. Definition of Vertical Farming

Vertical farming is an agricultural model where plants are cultivated on vertical planes instead of traditional horizontal fields (Kozai, 2013, 2018). This system utilizes multi-tiered shelves, towers, or indoor spaces with layered structures to maximize yield within a limited area (Despommier, 2010, 2011). By integrating controlled environment agriculture (CEA), vertical farming ensures optimal conditions for plant growth.

The technologies used in vertical farming enable plants to grow without soil by utilizing nutrient-rich solutions or water-based systems. Key approaches include hydroponics, aeroponics, and aquaponics (Al-Kodmany, 2018), which can be applied in urban settings such as abandoned buildings and rooftop gardens.

2.2. Vertical Farming Systems and Their Working Principles

Vertical farming systems leverage modern agricultural technologies and operate based on specific principles:

Hydroponic Systems: These systems replace soil with nutrient-rich water solutions, allowing plants to absorb essential nutrients directly (Van Delden et al., 2021). In vertical farming, hydroponic systems are often implemented on racks or towers, significantly conserving water and using up to 90% less than conventional agriculture (Benke & Tomkins, 2017).

Aeroponic Systems: Aeroponics involves suspending plant roots in the air and delivering nutrients through a fine mist. This technique enhances oxygen exposure, accelerates growth, and optimizes space and energy efficiency in vertical farming (Kalantari et al., 2018; Bayraklı & Altındisli, 2020).

Aquaponic Systems: Aquaponics integrates plant cultivation with fish farming (O'Sullivan et al., 2020). Fish waste serves as a natural nutrient source for plants, while plants help purify the water, creating a sustainable closed-loop system (Al-Kodmany, 2018).

These systems optimize water and energy usage, offering more sustainable agricultural practices.

2.3. Indoor Farming Technologies

Indoor farming is a crucial component of vertical farming, as it enables year-round production by controlling essential growth factors. The key technologies used in these systems include:

LED Lighting: Specialized, energy-efficient lighting systems designed to support plant photosynthesis (Despommier, 2010, 2011; Specht et al., 2014).

Sensor and Automation Systems: Technologies that monitor plant growth, optimize nutrient levels, and regulate environmental conditions (Kozai, 2018).

Climate-Controlled Environments: Adjustments in temperature, humidity, and CO_2 levels ensure optimal plant growth (FAO, 2019).

Indoor farming technologies make year-round, uninterrupted production possible, regardless of external conditions.

2.4. Advantages and Sustainability of Vertical Farming

Vertical farming offers multiple advantages over conventional agricultural methods:

Water Conservation: Hydroponic and aeroponic systems use up to 90% less water than traditional farming (Van Delden et al., 2021).

Local Production and Logistics Benefits: Urban food production reduces transportation-related carbon emissions (Godfray et al., 2010).

Higher Yields: Controlled environments enable higher crop productivity than open-field agriculture (Benke & Tomkins, 2017).

Environmental Sustainability: Reduced reliance on pesticides and herbicides minimizes negative environmental impacts (Kalantari et al., 2018).

The widespread adoption of vertical farming could enhance global food security while supporting environmental sustainability in urbanized societies.

3. Urban Applications of Vertical Farming

3.1. The Increasing Importance of Vertical Farming in Cities

Currently, more than 55% of the world's population resides in urban areas, and this proportion is expected to reach 68% by 2050 (UN, 2018). Rapid urbanization has made the integration of food production into urban environments inevitable. In this context, vertical farming has emerged as a significant solution that enables fresh and local food production in city centers. The reduction of agricultural land and the impacts of climate change further highlight the necessity and potential of vertical farming (Kalantari et al., 2018).

3.2. Successful Implementation Examples Singapore

Sky GreensSky Greens, one of the world's first commercial vertical farms, is located near the city center of Singapore. Established in 2012, this farm produces leafy greens such as lettuce and Chinese cabbage using rotating tower systems. The system offers a sustainable production model with low energy consumption (Pomeroy, 2013).

USA: AeroFarmsLocated in Newark, New Jersey, AeroFarms is one of the largest indoor vertical farms in the world. Utilizing artificial intelligence-supported sensor technologies and LED lighting systems, the company produces two million pounds of fresh vegetables annually without using soil. AeroFarms significantly contributes to environmental sustainability by using 95% less water in agricultural production (Al-Kodmany, 2018).

Japan: MiraiMirai, located in Japan, produces approximately 10,000 heads of lettuce daily on a 25,000-square-meter area. After the Fukushima nuclear disaster in 2011, the importance of indoor vertical farming for food security became more evident, leading to the rapid expansion of projects like Mirai (Kozai, 2013, 2018).

Türkiye: Emerging Vertical Farming ProjectsAlthough vertical farming in Türkiye is still in its early stages, urban agriculture projects are increasing. Particularly in major cities, hotels and restaurants have begun using vertical farming technologies to cultivate fresh produce. In key agricultural regions such as Antalya, the integration of technology with agricultural production is accelerating (Ergün et al., 2020).

Several successful vertical farming initiatives in Türkiye have marked significant progress in adopting modern agricultural techniques and promoting sustainable food production. Notable projects include:

Rooftop Gardens in IstanbulIn metropolitan areas such as Istanbul, the use of underutilized rooftop spaces for vertical farming is becoming increasingly common. Notably, rooftop farming projects developed by Istanbul Technical University aim to optimize urban spaces for local vegetable and fruit production (Ergün et al., 2020).

Indoor Vertical Farming R&D Center in IstanbulThe Istanbul Provincial Directorate of Agriculture and Forestry initiated the Indoor Vertical Farming Application and R&D Center Project to conduct soilless farming with minimal water consumption. A cooperation protocol was signed with Istanbul Fertilizer Industry Inc. (IGSAŞ), and a 700-square-meter facility was planned for construction on the eighth underground floor of a parking lot in Kağıthane district. This center aims to control all plant growth processes from seed to harvest and share the obtained data with the private sector.

Plant Factory in IstanbulPlant Factory, located on the -4th floor of the IstinyePark shopping mall in Istanbul, has the capacity to harvest 900,000 products annually. The facility primarily cultivates lettuce varieties and other leafy greens, which are harvested daily and delivered to consumers.

These projects represent successful examples of vertical and soilless farming applications in Türkiye, contributing significantly to sustainable and efficient food production.

3.3. Rooftop Gardens and Container Farming

Another method of implementing vertical farming in urban areas is through rooftop gardens and container farming. Rooftop gardens provide environmental benefits while creating spaces for local food production. For example, Nature Urbaine in Paris, the largest rooftop farm in Europe, produces approximately 20 tons of vegetables annually (Buehler & Junge, 2016).

Container farming offers a mobile production model in cities. In addition to providing logistical flexibility, vertical farms in containers serve as a low-cost entry point for urban agriculture (Gentry, 2019).

3.4. The Role of Vertical Farming in Cities

Vertical farming presents an effective solution for ensuring access to fresh and reliable food in urban areas with increasing populations. This system allows for the efficient use of idle spaces and enhances urban food production capacity. Furthermore, it serves as a tool for raising public awareness and involving urban residents in the production process (Kalantari et al., 2018).

4. Advantages of Vertical Farming for Urban Vegetable Cultivation

4.1. Access to Fresh and Nutrient-Rich Food

Vertical farming facilitates quick access to fresh and nutrient-rich food due to its applicability in urban centers. In traditional agricultural systems, the transportation of vegetables and fruits to consumers can take days or even weeks. In contrast, vertical farming enables products to be delivered to local markets immediately after harvest (Al-Chalabi, 2015).

This ensures the preservation of nutritional value and contributes to reducing food waste. Additionally, by minimizing logistical requirements in the supply chain, vertical farming allows products to reach consumers at lower costs.

4.2. Efficiency in Water, Energy, and Land Utilization

Vertical farming provides a sustainable production model by maximizing efficiency in water, energy, and land use:

Water Conservation: Hydroponic and aeroponic systems save up to 90% more water compared to traditional agriculture. The closed-loop system ensures water is continuously recycled, preventing wastage (Despommier, 2011; Van Delden et al., 2021).

Energy Efficiency: The use of low-energy consumption technologies, such as LED lighting, minimizes energy use and enhances sustainability (Kozai, 2013). Moreover, integrating renewable energy sources can further increase energy independence.

Optimized Land Use: Unlike conventional farming, which requires vast land areas, vertical farming maximizes production efficiency within small spaces through multi-layered structures. For instance, a vertical farm in Japan produces up to 50 times more crops per acre compared to traditional farming (Kozai, 2013).

4.3. Logistical Convenience and Reduction of Carbon Footprint

Growing vegetables in urban centers shortens the food supply chain, reducing both logistics costs and carbon footprint:

Shorter Supply Chain: Traditional agriculture often involves long-distance transportation of produce, which increases logistics expenses and shortens shelf life. Vertical farming eliminates these disadvantages by enabling localized production.

Reduction of Carbon Emissions: The transportation of agricultural products over long distances relies on fossil fuels, contributing to carbon emissions. By relocating food production to urban areas, vertical farming significantly reduces greenhouse gas emissions associated with transportation (Kalantari et al., 2018).

4.4. Environmental Sustainability and Reduction of Pesticide Use

As a closed agricultural system, vertical farming promotes environmental sustainability and reduces chemical use, ensuring safer food production:

Reduced Pesticide Use: The controlled environment of vertical farms minimizes the spread of pests and diseases, significantly reducing the need for pesticides. This benefits both human health and the ecosystem (Beacham et al., 2019; Specht et al., 2014).

Minimized Soil Degradation: Since hydroponic and aeroponic systems do not require soil, issues such as erosion, soil pollution, and contamination of natural water sources by agricultural chemicals are prevented.

Climate Change Mitigation: Lower greenhouse gas emissions, efficient water use, and the incorporation of sustainable energy sources make vertical farming an environmentally friendly solution (Despommier, 2011).

4.5. Food Security and Independent Production

The global population is projected to reach 9.7 billion by 2050 (UN, 2018), increasing concerns about food security. Vertical farming strengthens food security by promoting local production and reducing dependency on external supply chains.

Resilience to Climate Change and Natural Disasters: Since vertical farming takes place in controlled indoor environments, it is not affected by climate change, droughts, or natural disasters.

Food Supply Stability During Crises: Urban vertical farms provide a secure food supply chain, mitigating disruptions caused by global pandemics, conflicts, or logistical failures.

4.6. Economic Contributions and Investment Opportunities

Vertical farming offers significant economic benefits for urban economies:

Job Creation and Employment Opportunities: Indoor agricultural production generates a demand for a wide range of jobs, from food production to marketing. For example, AeroFarms in the United States has provided employment opportunities for hundreds of individuals in Newark alone (Kalantari et al., 2018).

Investment and Entrepreneurial Prospects: The global demand for sustainable agricultural technologies is rising. In 2020, investments in the vertical farming sector exceeded $1 billion (Grand View Research, 2021), making it an attractive sector for entrepreneurs.

4.7. Social Contributions and Educational Opportunities

Beyond being a production model, vertical farming also serves as an educational tool and raises public awareness:

Education and Awareness: Vertical farming systems are utilized in schools and community projects to promote environmental awareness and educate younger generations on sustainable agricultural practices (Buehler & Junge, 2016).

Community Engagement: Community-based vertical farming projects encourage active participation in food production, enhancing environmental consciousness and fostering sustainable urban living.

4.8. Health and Well-Being Benefits

Vertical farming plays a role in improving dietary habits in urban areas:

Fresher and More Nutritious Produce: Due to shorter supply chains, products can be delivered to consumers without the need for preservatives that extend shelf life (Kozai, 2018).

Prevention of Obesity and Chronic Diseases: Increased consumption of fresh fruits and vegetables supports healthy eating habits, helping to prevent obesity and chronic diseases (Beacham et al., 2019).

5. Challenges Facing Vertical Farming

5.1. High Initial Investment Costs

Vertical farming projects require substantial initial investment. Particularly, equipment such as LED lighting systems, sensors, and automation technologies significantly increase project costs (Kalantari et al., 2018). Additionally, establishing the necessary infrastructure for indoor farming is more expensive compared to traditional agriculture, posing a significant barrier, especially for small-scale entrepreneurs (Benke & Tomkins, 2017).

5.2. Technical Expertise and Competency Requirements

Vertical farming relies on advanced technologies, necessitating a high level of technical knowledge and expertise. The installation, operation, and maintenance of these systems require professionals with expertise in both engineering and agriculture (Beacham et al., 2019; Despommier, 2011). This requirement may complicate the recruitment process and increase operational costs.

5.3. Energy Consumption and Costs

Artificial lighting and climate control systems used in vertical farming result in high energy consumption. In large-scale facilities, energy costs constitute a significant portion of total production expenses. While integrating renewable energy sources can mitigate these costs, the technological investments required for such integration further increase overall expenditures, hindering the widespread adoption of vertical farming (Benke & Tomkins, 2017; Kozai, 2013).

5.4. Marketing and Consumer Habits

The prices of vertically farmed products are generally higher than those produced through conventional methods, making consumer adoption challenging. Given the growing preference for organic and naturally grown products, some consumers may have reservations about crops grown under artificial lighting in controlled environments (Besthorn, 2013). Furthermore, a lack of consumer awareness regarding vertical farming may pose additional marketing challenges (Buehler & Junge, 2016).

5.5. Lack of Natural Light and Flavor Quality

Since vertical farming is conducted in enclosed environments, plants are deprived of natural sunlight. Although LED lighting supports photosynthesis, it may not fully replicate the beneficial effects of natural sunlight on plant growth. Some studies suggest that this limitation may negatively impact the flavor profile of crops (Beacham et al., 2019).

5.6. Large-Scale Implementation Challenges

While vertical farming offers an effective solution in urban areas with limited space, it remains inadequate when compared to large-scale agricultural production in rural areas. The production of staple crops such as grains is technically and economically less feasible within vertical farming systems (Al-Chalabi, 2015). This suggests that vertical farming may only fulfill a portion of global food production needs.

5.7. Environmental Impacts

Although vertical farming has the potential to enhance environmental sustainability, its high energy consumption may contribute to a significant carbon footprint. Therefore, improving energy efficiency and integrating renewable energy sources are crucial for minimizing environmental impacts (Kalantari et al., 2018).

6. Future Perspectives

6.1. Technological Advancements in Vertical Farming

Technological advancements will play a crucial role in the future of vertical farming. The integration of artificial intelligence (AI), the Internet of Things (IoT), and robotic systems can optimize production processes, enhancing efficiency. AI-driven systems, for example, can analyze plant needs in real time and manage irrigation, fertilization, and lighting processes more effectively (Kalantari et al., 2018).

Moreover, IoT technology allows farms to be remotely monitored and controlled, reducing the reliance on manual labor while increasing productivity (Gentry, 2019).

6.2. Integration of Renewable Energy

The high energy consumption in vertical farming can be mitigated through the adoption of renewable energy sources. Solar power, wind energy, and biogas technologies offer viable solutions to minimize the carbon footprint of vertical farming. For instance, some vertical farms in Japan already meet a significant portion of their energy needs through solar panels (Kozai, 2013).

6.3. Contribution to Global Food Security

The United Nations projects that the global population will reach 9.7 billion by 2050, raising serious concerns about food security (UN, 2018). Vertical farming can support global food security by increasing urban production capacity. Additionally, its resilience to extreme weather conditions and natural disasters enhances agricultural stability (Beacham et al., 2019).

6.4. Sustainable Cities and Smart Agriculture

Vertical farming is regarded as an integral component of future sustainable cities. Integrating vertical farming projects into urban planning can yield both environmental and social benefits. Particularly, the widespread adoption of vertical farming within smart city frameworks can enhance waste management, energy efficiency, and public awareness (Buehler & Junge, 2016).

6.5. Policy and Government Support

The widespread adoption of vertical farming will require the support of policymakers. Government incentives, tax reductions, and favorable regulations can facilitate the broader acceptance of this innovative agricultural method. Furthermore, increased investment in research and development (R&D) for vertical farming projects will be crucial for advancing the industry (Grand View Research, 2021).

6.6. Education and Public Awareness

Public awareness plays a vital role in the expansion of vertical farming. Educational programs in academic institutions can foster interest in sustainable agricultural techniques among future generations. Additionally, community-based vertical farming projects can engage individuals in food production, promoting local participation (Al-Chalabi, 2015).

Conclusion and Recommendations

Vertical farming emerges as an innovative solution for sustainable agriculture in an era of rapid urbanization and escalating environmental challenges. Addressing global issues such as limited agricultural land, water scarcity, and climate change, this system offers an effective alternative by promoting land and water conservation while enhancing energy efficiency and nutrient solution optimization. In addition to transforming agricultural production processes, vertical farming facilitates access to fresh and nutrient-rich food in urban areas and fosters public awareness, encouraging greater engagement in agricultural activities.

However, the widespread adoption of vertical farming faces several challenges. High initial investment costs, substantial energy consumption, and the requirement for technical expertise constitute major limitations to its large-scale implementation. Nevertheless, the integration of advanced technologies such as artificial intelligence, the Internet of Things (IoT), and renewable energy sources can help overcome these obstacles. Furthermore, government policies and incentives can enhance the economic viability of vertical farming projects by making them more accessible. Supportive policies from local governments, the dissemination of vertical farming technologies to low-income countries, and the encouragement of innovation-driven research and development (R&D) efforts are crucial for accelerating the global adoption of this system. Community-based projects can further promote public participation in agricultural production, thereby fostering environmental awareness and encouraging sustainable lifestyles.

In conclusion, for vertical farming to become a significant component of future agricultural production, technological advancements, governmental support, and public awareness initiatives must progress in tandem.

References

Al-Chalabi, M. (2015). Vertical farming: Skyscraper sustainability? Sustainable Cities and Society, 18, 74-77. https://doi.org/10.1016/j.scs.2015.06.003

Al-Kodmany, K. (2018). The vertical farm: A review of developments and implications for the vertical city. Buildings, 8(2), 24. https://doi.org/10.3390/buildings8020024

Bayraklı, M., & Altındişli, A. (2020). Şehirde sürdürülebilir tarım: Dikey tarım sistemlerinin rolü. Tarım ve Teknoloji Dergisi, 12(3), 45-57.

Beacham, A. M., Vickers, L. H., & Monaghan, J. M. (2019). Vertical farming: A summary of approaches to growing skywards. The Journal of Agriculture and Food Research, 2, 100032. https://doi.org/10.1016/j.jafr.2019.100032

Benke, K., & Tomkins, B. (2017). Future food-production systems: vertical farming and controlled-environment agriculture. Sustainability: Science, Practice and Policy, 13(1), 13-26. https://doi.org/10.1080/15487733.2017.1394054

Besthorn, F. H. (2013). Vertical farming: Social work and sustainable urban agriculture in an age of global food crises. Australian Social Work, 66(2), 187-203. https://doi.org/10.1080/0312407X.2012.715658

Buehler, D., & Junge, R. (2016). Global trends and current status of commercial urban rooftop farming. Sustainability, 8(11), 1108. https://doi.org/10.3390/su8111108

Despommier, D. (2010). The vertical farm: Feeding the world in the 21st century. St. Martin's Press.

Despommier, D. (2011). The vertical farm: Feeding the world in the 21st century. Thomas Dunne Books.

Ergün, B., Yıldırım, İ., & Şen, S. (2020). Türkiye'de şehir tarımı ve dikey çiftlikler. Tarım Bilimleri Dergisi, 26(3), 212-219.

FAO. (2019). The state of food and agriculture 2019. Food and Agriculture Organization of the United Nations. Retrieved February 25, 2025, from https://openknowledge.fao.org/server/api/core/bitstreams/11f9288f-dc78-4171-8d02-92235b8d7dc7/content

Gentry, R. (2019). Portable farming: The growth of container farms in urban environments. Urban Agriculture Magazine, 35(2), 20-28.

Godfray, H. C. J., et al. (2010). Food security: The challenge of feeding 9 billion people. Science, 327(5967), 812-818. https://doi.org/10.1126/science.1185383

Graamans, L., Baeza, E., Van Den Dobbelsteen, A., Tsafaras, I., & Stanghellini, C. (2018). Plant factories versus greenhouses: Comparison of resource use efficiency. Agricultural Systems, 160, 31-43. https://doi.org/10.1016/j.agsy.2018.01.003

Grand View Research. (2021). Vertical farming market size, share & trends analysis report. https://www.grandviewresearch.com/industry-analysis/vertical-farming-market

Kalantari, F., Tahir, O. M., Joni, R. A., & Fatemi, E. (2018). Opportunities and challenges in sustainability of vertical farming: A review. Journal of Landscape Ecology, 11(1), 35-50. https://doi.org/10.2478/jlecol-2018-0004

Kozai, T. (2013). Resource use efficiency of closed plant production systems with artificial light. Journal of Environmental Horticulture, 31(1), 49-54.

Kozai, T. (2018). Smart plant factory: The next generation indoor vertical farms. Springer.

O'Sullivan, C. A., et al. (2020). Innovations in sustainable agriculture: Vertical farming and precision agriculture. Current Opinion in Environmental Science & Health, 13, 18-23. https://doi.org/10.1016/j.coesh.2019.10.005

Pomeroy, J. (2013). Growing in the city: Urban agriculture in Singapore. Urban Design International, 18(2), 140-149. https://doi.org/10.1057/udi.2013.10

Specht, K., et al. (2014). Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. Agriculture and Human Values, 31(1), 33-51. https://doi.org/10.1007/s10460-013-9448-4

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences, 108(50), 20260-20264. https://doi.org/10.1073/pnas.1116437108

UN. (2018). World urbanization prospects: The 2018 revision. United Nations Department of Economic and Social Affairs.

Van Delden, S. H., SharathKumar, M., Butturini, M., Graamans, L. J. A., Heuvelink, E., Kacira, M., & Stanghellini, C. (2021). Vertical farming at high latitudes: Present status and perspectives. Frontiers in Plant Science, 12, 607731. https://doi.org/10.3389/fpls.2021.607731