THE ANNALS OF "DUNAREA DE JOS" UNIVERSITY OF GALATI
FASCICLE IX. METALLURGY AND MATERIALS SCIENCE
N°. 4 - 2025, ISSN 2668-4748; e-ISSN 2668-4756
Article DOI: https://doi.org/10.35219/mms.2025.4.11

MODERNISATION OF IRRIGATION SYSTEMS – A SUSTAINABLE SOLUTION FOR EFFICIENT WATER RESOURCE MANAGEMENT IN AGRICULTURE

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ABSTRACT

In the current context, marked by accelerated climate change, population growth, and the development of anthropogenic activities, pressure on water resources is increasing. Therefore, the need to develop efficient and sustainable agriculture through effective water resource management is becoming a priority at both global and national levels. Romania is increasingly facing challenges in adapting the agricultural sector to new climatic conditions. These conditions are characterized by increasingly pronounced fluctuations in precipitation and a rising frequency of drought years – characteristics that negatively affect crop productivity and stability.

This article aims to analyse the benefits of modernizing irrigation technologies, focusing on innovative, smart, and environmentally friendly solutions, such as precision irrigation. An innovative alternative solution is examined, namely the use of fog collectors as a complementary method of passive water collection, with potential for application in favourable microclimates, including the hilly areas of Romania.

KEYWORDS: irrigation, water stress, fog collectors

1. Introduction

Although 71% of the Earth's surface is covered with water, only 2.53% is freshwater. Of this percentage, 68.7% is in solid form at the two poles and in high mountains, 30.1% is groundwater, meaning that only 1.2% of the planet's freshwater volume actively participates in sustaining and prospering human life and civilization [1].

It is well known that no organism on our planet can survive without water. People's biological needs include drinking water and basic hygiene, but in today's society, water is also necessary for industry, agriculture, hydroelectric power, etc. In addition to this, water is an indispensable element of the landscape for recreation, navigation, fishing, and other activities.

Romania's hydrographic network is 78,905 km long and evenly distributed, with 98% of the rivers in Romania originating in the Carpathian Mountains [2]. An important network of rivers crosses the state border, and the Tisa, Prut, and Danube form part of Romania's border. The main rivers are the Mureș (761 km), Prut (742 km), Olt (615 km), Siret (559 km), Ialomița (417 km), Someș (376 km), and Argeș (350 km) [2, 3].

The Danube River is by far the most important source of fresh water in Romania, ranking 23rd in the world with a flow rate of approximately 6,450 m3/s and a total length of 2860 km, of which 1075 km lie within Romania [1].

Romania has a significant amount of groundwater, approximately 9.6 billion m^3, of which 4.66 billion m^3 is usable and 4.9 billion m^3 represents the deep reserves [4].

According to the Environmental Report of the National Strategy for Preventing and Combating Desertification and Land Degradation, in 2021, there were 143 groundwater bodies, divided as follows:

- 115 groundwater bodies;
- 28 deep groundwater bodies.

Water quality, determined by its organoleptic, physical, chemical, biological, and bacteriological characteristics, is continuously monitored at input points (natural waters) and output/effluent points (discharges from various outlets).

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With Romania's accession to the European Union, it was necessary to implement 18 Directives and 2 Decisions on integrated water monitoring.

Three types of monitoring programs are applied to surface waters:

- Surveillance monitoring assesses the status of all water bodies in river basins.
- Operational monitoring is an integral part of surveillance monitoring and is intended for water bodies at risk of not meeting protection objectives.
- Investigative monitoring aims to identify the causes of exceedances of the limits set in the quality standards.

Two types of monitoring programs are implemented for groundwater:

- Quantitative monitoring.
- Qualitative monitoring, which may be surveillance and/or operational [5].

According to the assessment carried out within the Updated National Management Plan for the National Portion of the Danube River Basin, the ecological status of surface waters is good in terms of chemical quality. The assessment was carried out on 3025 water bodies and found that 97.65% are in good chemical status, while the remaining 2.35% do not achieve good chemical status [2].

Figure 1 shows the ecological status and ecological potential of surface water bodies at the national level. The green lines represent water bodies in good condition, the yellow lines represent water bodies in moderate chemical condition, and the red lines represent water bodies that do not achieve good chemical status.

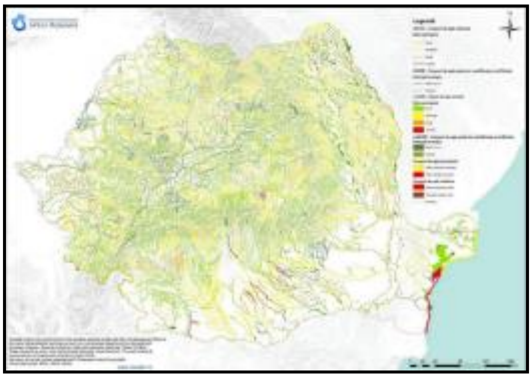

Fig. 1. *Ecological status and ecological potential of surface waters in Romania* [2]

2. The importance of water

2.1. Use of water resources

Since ancient times, humans have understood that without water, their bodies cannot function, and that without it, neither animal nor plant food can be obtained. Therefore, waterways have been used to provide the necessary water, but also for transportation (navigation). Historical data confirms that the great ancient civilizations developed on the banks of the Nile, Tigris, Euphrates, Indus, and other rivers. The links between humans, society, and water are extremely complex and, as society developed, humans were compelled to intervene in waterways, thus causing changes in both riverbed processes and water quality.

Conclusive evidence of water collection and use systems remains in various parts of the world. Wells, aqueducts, navigation channels, dams, drainage, and irrigation systems are just some examples, and they prove that in order to obtain water, people throughout history have used all their intellectual capacity in conjunction with the technical means available at the time.

In modern society, the need for water is directly linked to human actions that transform the environment in order to easily obtain what is necessary for life, for urbanization and industrialization, or for more intensive agriculture.

In Europe, approximately 75% of the water extracted comes from surface water (rivers and reservoirs), and the remaining 25% from groundwater. The highest quantities are extracted during the growing season [2].

The main source of water in Romania comes from inland rivers. Although there are quite many natural lakes, they have small volumes, except Lake Razelm and Sinoe.

At the European level, large quantities of water are used in activities such as agriculture (58%), cooling in energy processes (18%), mining (11%), and households (10%). It follows that agriculture is the economic sector with the highest consumption of water resources [5].

Although at the European level, the largest volume of water collected from surface sources is used in agriculture. In Romania, the industry uses the largest proportion of water resources, followed by agriculture. Between 2015 and 2020, water requirements were analysed for three sectors: industry, agriculture, and population. The data obtained from the analysis are presented in Figure 2 and shows that the industry has the highest water consumption. It can also be seen that demand is higher than the available withdrawal level for all three categories analysed, except for 2020, in which the amount of water withdrawn for agriculture was higher than demand, indicating water loss in this area.

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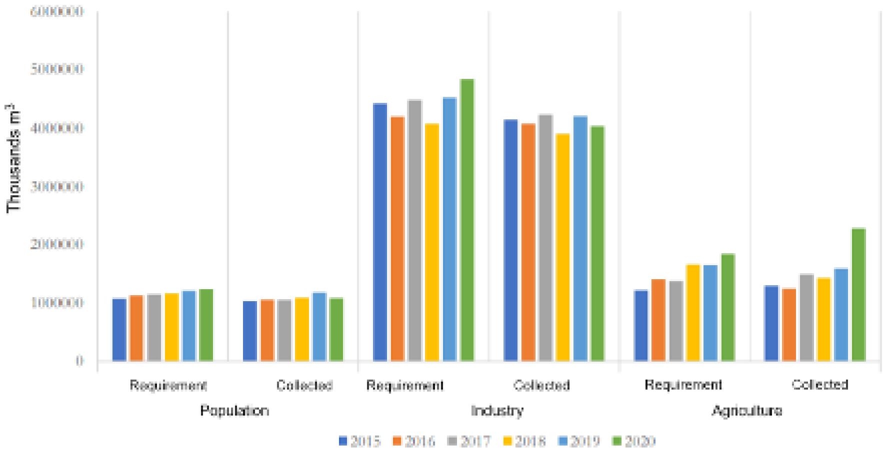

***Fig. 2.** Surface water requirements/quantity sampling* [2]

Regarding groundwater, in Romania, the largest amount captured is used to supply water to the population, followed by industry, agriculture, and other activities. Figure 3 shows the distribution of the volume of groundwater abstracted and its use at the level of river basins. The colours in the figure indicate each category analysed: blue for the population, green for industry, and yellow for agriculture and other activities. It should be noted that the Dobrogea-Litoral basin has the largest amount used by the population, and the Olt River basin uses the entire volume of groundwater extracted only for the population and industry.

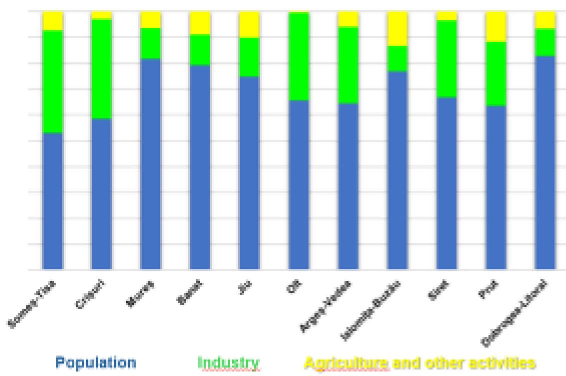

***Fig. 3.** Groundwater use at the level of watersheds in Romania* [3]

2.2. Pressure on water bodies

Factors such as climate change, reflected in rising average temperatures and the frequent occurrence of extreme weather events (including drought), population growth, and economic development are amplifying water shortages around the world, both seasonally and over extended periods.

In the European Union, a large part of the territory is already affected by water abstraction exceeding available reserves, leading to increasing water stress. Water stress is the ratio between total water abstraction and available renewable surface and groundwater reserves [2].

According to a study conducted by the World Bank, over the last 55 years, there has been a 17% decrease in renewable water reserves per capita at the European level [2]. This phenomenon is partly caused by population growth, but economic pressures and climate change also significantly contribute to the intensification of water shortages, which are felt seasonally or throughout the year in certain regions of the European Union. Forecasts for 2030 show a significant increase in the areas of Europe where water stress will intensify. Figure 4 shows the situation in European regions in 2021 as a reference for the 2030 forecasts. It can be seen that in Romania, there are regions with high and very high-water stress, especially in the northeast, east, and southeast. In the northwest, there are areas with low to medium and medium to high water pressure, but these occupy smaller areas.

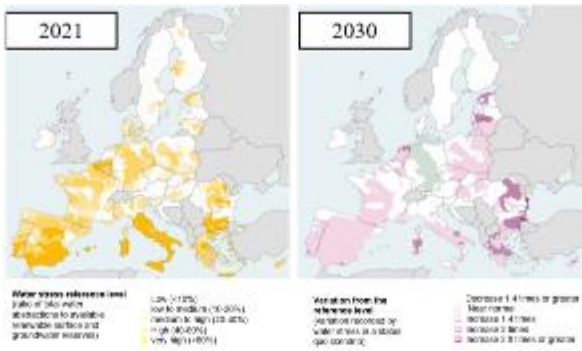

***Fig. 4.** Water stress in the EU in 2021 and projections for 2030* [6]

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Agriculture is closely linked to water availability. Irrigation provides farmers with protection against rainfall variability, promoting increased productivity, yield, and crop quality. However, it also puts significant pressure on water reserves. Research shows that the greatest pressure is generated in Spain (20-40%), followed by France and Bulgaria with 10-20% for surface water. In the case of groundwater, Hungary ranks first with a percentage of more than 40%, followed by Spain and Greece (20-40%). In Romania, there are no water bodies under pressure, but as mentioned above, most of the water collected in our country is used in industry.

Therefore, water is an important resource for life, ecological balance, and economic development, which is why its management must be efficient for the future of our planet. The primary source of fresh water is surface water and groundwater, but their quality and availability are threatened by overuse and poor management.

Forecasts for 2030 highlight the worrying reality that freshwater reserves are declining, and urgent measures are therefore needed to conserve and use this resource sustainably.

Investments in modern technologies can help optimise excessive consumption in agriculture and protect water resources for future generations, which is in line with the principle of sustainable development. Therefore, it is very important that every individual and every government adopt a responsible attitude to ensure a balance between current needs and the protection of this essential resource for life, namely water.

3. Efficient water management in irrigation

Water is an indispensable resource for life, but it is also one of the most vulnerable elements to climate instability. Globally, agriculture uses over 70% of available water (rivers, lakes, groundwater, etc.) Conventional irrigation methods are inefficient and generate high losses, contributing to soil degradation and water resource depletion. In Romania, most of the irrigation systems built during the communist regime have been abandoned or have suffered major damage. Moreover, the lack of functional infrastructure seriously affects agricultural production, especially in the southern and eastern regions of the country.

Water management in irrigation involves the application of practices and technologies designed to reduce water consumption and losses through evaporation, runoff, and uncontrolled infiltration, as well as to improve the efficiency of irrigation systems. Measuring soil moisture and water flow, rational irrigation scheduling, and the use of modern technologies are important in the development of sustainable and efficient irrigation systems [7].

Irrigation efficiency is a fundamental concept in irrigation engineering, used to characterise irrigation performance, evaluate water use in irrigation, and promote more efficient use of water resources, especially those used in agriculture and green space management [8].

Irrigation efficiency is defined by the following elements:

- irrigation system performance;
- uniformity of water application;
- crop response to irrigation.

Each element of irrigation efficiency can vary in scale and time.

The spatial scale can range from very small units, such as a single irrigation application device (e.g., a siphon tube, pipe valve, sprinkler, or micro-irrigation emitter) to somewhat larger units, such as an irrigation set (a basin plot, a group of furrows, a sprinkler line, or a micro-irrigation lateral). On an even larger scale, it can include extensive areas such as an agricultural field, an entire farm, or an irrigation lateral [8].

3.1. Fog collectors – an alternative water source in arid areas

Climate change poses a major challenge for agriculture. Water resources and crop stability are key priorities in policies to prevent and mitigate extreme events.

Unconventional water resources are considered viable solutions to meet or supplement irrigation water demand in water-scarce regions. Technologies for collecting water from the atmosphere must be efficient, affordable, and stable to ensure long-term irrigation, even in seasons with low rainfall.

Although the quantities of water obtained by methods such as dew collection or condensation are relatively small, they can be a valuable source of water, especially in arid and semi-arid areas where traditional water resources are limited or difficult to access. Condensation irrigation systems rely on atmospheric moisture and are specifically designed for regions with water shortages.

Below are some fog collectors that use atmospheric moisture to irrigate high-value crops, such as vegetables for processing and fresh consumption (peppers, bell peppers, early tomatoes, etc.) or aromatic and medicinal plants (lavender, basil, mint etc.).

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3.1.1. How it works

Fog collectors are passive systems, generally constructed from polyethylene or nylon nets, mounted vertically on a support structure (metal or wood). They work by intercepting water droplets from the fog, which condense on the mesh threads, accumulate, and then drain into a collection trough, from which they are directed by gravity to a storage tank [9].

Research suggests that these fog collectors work best in coastal areas, where water can be collected as fog is pushed inland by the wind.

But they can also be adapted to hilly areas, such as the Vrancea region, where frequent fog formation is favoured by low nighttime temperatures, which cause water vapor to condense, as well as by the thermal inversions characteristic of the terrain. These conditions are suitable for the implementation of fog collectors, which can harness atmospheric humidity as an additional source of water for irrigation, especially during periods of water shortage.

A standard fog collector consists of the structural and functional elements shown in Figure 5, each of which plays an important role in the efficiency of the process of water collection from the atmosphere.

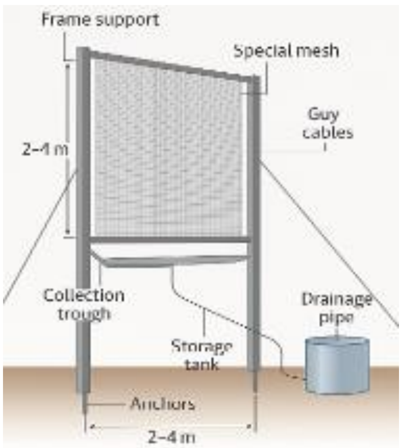

Fig. 5. *Schematic of a standard fog collector*

Support frame – is the basic structure on which the collection net is mounted. It can be made of galvanized metal profiles or treated wood for outdoor use. The dimensions of the frame may vary depending on the needs, but the standard one, shown in Figure 5, has a height between 2 and 4 meters and a width between 2 and 4 meters. The frame ensures the stability of the system in strong wind conditions and positions the net so that it captures fog currents as efficiently as possible.

Special net – generally, the net used in collectors is the Raschel type or other variants of high-density net (HDPE), with 1-2 mm mesh, to easily retain fine water droplets. The surface area of a collector's net varies, depending on the application, between 4 and 8 m2 (for individual or experimental use) and 40 m^2 (for community or agricultural systems).

Collection gutter – mounted at the base of the net, at a slight angle of approximately 5-7° from the horizontal, it collects the water that drains from the net. It is made of PVC, stainless steel, or plastic, all of which is corrosion-resistant, and the width of the gutter can be 10-15 cm.

The drainage pipe, with a diameter of DN32-DN50 mm, transports water from the gutter to the storage tank. In the case of an assembly containing several collectors, these pipes are joined together in a main collector pipe (spine-type system), which descends gravitationally from the slope to the storage tank.

Storage tank – this can be a plastic container approved for water or a semi-buried cistern with a volume of between 200 and 1000 litres/collector, depending on the estimated yield and local needs. For collective networks, larger modular tanks can be used.

Anchors and tension cables – for the safety of the collector in strong wind conditions, the frame is secured with metal anchors or concrete stakes and further stabilized with galvanized steel tension cables anchored in the ground at a distance of 1-2 meters from the base.

Optionally, the collector can be equipped with a simple filtration system (screen or pre-filter at the tank inlet) to prevent contamination with particles or debris from the net, and overflow valves or taps for water collection [9].

Research on fog water harvesting has focused on developing more efficient and durable mesh materials. The standard Raschel mesh (Figure 6 A) recorded a daily average water collection of 1.235 L/m^2 and is considered the benchmark in the field. The Aluminet mesh, made of high-density polyethylene with an aluminium coating, achieved an average of 96% of the volume collected by the Raschel mesh and was preferred due to its good performance at low wind speeds. In areas with very strong winds, such as South Africa, special nets made of polymers woven with stainless steel (Figure 6 B) have been developed, which, although less efficient at collection, offer superior durability and lower maintenance costs, demonstrating that, under certain conditions, the reliability of the material can be more important than maximum efficiency in collecting fog water. Figure 6 C shows another type of material, namely a prototype 3D polymer net – an experimental design that uses a three-dimensional structure to improve fog capture performance [10].

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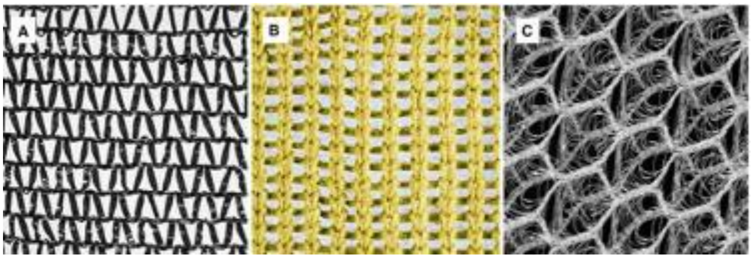

Fig. 6. *Types of mesh for mist catcher: A) Single layer Raschel mesh; B) Stainless steel reinforced poly-yarn mesh; C) 3D polymer mesh prototype*

3.1.2. Optimal operating conditions for fog collectors

The efficient operation of fog collectors largely depends on the climate and terrain of the region where they are installed. The hilly area of Vrancea county, where the Pufești-Ruginești agricultural area analysed in this case study is located, has climatic (fog, wind, etc.) and terrain characteristics that are favourable for the adoption of this technology.

According to data provided by Direcția Silvică Vrancea (the Vrancea Forestry Directorate), the hilly area of Vrancea experiences between 100 and 120 days of fog per year, with a higher incidence during the cold season (autumn, winter, and early spring) [11]. The local microclimate, influenced by the relief and the proximity of forests, maintains a high relative humidity, favouring the formation of fog, especially in depressions and valleys. The fog observed in this area is generally dense and rich in fine water droplets, with an estimated diameter of 0.005-0.05 mm, which is considered optimal for fog collectors [11]. Persistent fog provides an additional supply of water, which is especially useful during dry periods or when precipitation is below average.

Meteorological statistics for the area of interest (Pufești-Ruginești) show that the average wind speed ranges between 1.2 and 3.8 m/s in autumn and spring. These are ideal values for collecting fog with special nets, without significant losses due to strong currents [11].

In the hilly region of Vrancea, there is a marked temperature contrast between day and night, especially in April-May and September-November, which favours condensation and the maintenance of fog during the night and morning.

Taking into account these climatic data (number of days with persistent fog, wind speed etc.), it is estimated that a fog collector with an area of 40 m^2 installed on a ridge exposed to prevailing winds could collect between 160 and 280 L of water/day during favourable periods. This contribution does not cover the entire irrigation needs for large areas, but it can effectively be used to supplement irrigation in nurseries or to maintain soil moisture during the emergence of the main crops.

The integration of a fog collector in the Pufești-Ruginești agricultural perimeter, as an auxiliary system, can contribute to the diversification of water sources and increase the resilience of local farms to drought. This can reduce pressure on conventional resources and lower the operating costs of the irrigation system.

3.1.3 Maintenance, operation, and costs of fog collectors

Once correctly installed, fog collection systems require simple operation and minimal maintenance, especially if users have been directly involved in the installation. Long-term success depends on a routine maintenance program and quality control of collected water. Some of the activities included in the maintenance program are:

- Periodic checking of cable tension and fasteners to prevent structural damage;
- Inspection and repair of nets, which can be affected by tears or dust accumulation reducing efficiency and affect water quality;
- Cleaning the gutters, screens, and pipes to prevent blockages and biological contamination;
- Sanitizing storage tanks with disinfectant solutions and preventing the entry of insects or other impurities;
- Monitoring the chlorine level in the water as a method of controlling microbiological risks [12].

The installation costs of fog collector systems vary considerably depending on the location, climatic conditions, and technical specifications of the project. For example, in a project carried out in the Antofagasta region of Chile, the installation cost of a fog collector was estimated at approximately 83 EUR/m^2 of net. In another project in northern Chile, a 40 m^2 collector had a total cost of around 348 EUR (of which 207 EUR was for materials, 58 EUR for labour, and 36 EUR for contingencies). This system had an average yield of 3.0 L/m^2/day [12].

Both capital and operating costs are influenced by several factors, including the efficiency of the collection system, the length of the pipes, and the volume of the storage tanks. For example, for a system with an efficiency of 2.0 L/m^2/day, the unit cost of water production was estimated at 4.40 EUR/1000 L, while an increase in efficiency to 5.0 L/m^2/day would reduce this cost to just 1.75 EUR/1000 L [12].

3.1.4. Application possibilities in Romania

Although Romania does not have microclimates identical to those in desert regions, there are hilly and mountainous areas where fog collectors can be beneficial, such as the sub-Carpathian regions (Vrancea, Buzău, Vâlcea, etc.), mountain depressions (Apuseni, Făgăraş, etc.), or the Black Sea coast (where fog is frequent in winter and spring).

The Pufeşti-Ruginești area (Vrancea county) has a number of geographical and climatic characteristics that are favourable for the implementation of fog collectors:

- hilly terrain with altitudes ranging from 200 to 500 m,
- frequent fog (estimated at 100 – 120 days/year),
- the orientation of the valleys, which favours the accumulation of moisture-laden air currents and creates a favourable environment for the condensation of water vapor on the surfaces of the collectors.

Based on these factors and analysing the yields observed in international projects, a potential collection of 4 - 7 L/m^2/day is estimated during the active season. Therefore, a system consisting of 40 m2 collectors could provide a constant supply of water to supplement the irrigation system. This can help to reduce pressure on conventional sources and increase the resilience of local agriculture in the face of water shortages.

The role of fog collectors is complementary in mixed irrigation systems. They can supply water for greenhouses and nurseries by feeding buffer tanks in drip systems, or they can partially cover precision watering and replenishment needs during dry periods.

3.2. Pilot project: Fog collection system - Pufești-Ruginești area, Vrancea

Considering both the climatic conditions in the Pufeşti-Ruginești area and the need to supplement water resources for irrigating sensitive crops with added value, a pilot project is proposed to collect water from fog for a 5-hectare plot dedicated to growing peppers, irrigated by drip irrigation.

3.2.1. Estimation of water requirements and collector efficiency

According to specialised studies, in peppers, daily evapotranspiration (ETc) is 4 - 6 mm/day during peak periods, which corresponds to 4 - 6 L/m^2/day in a well-managed system [13]. Therefore, if we estimate an average daily water consumption during the growing season of 5 L/m^2/day for an area of 5 hectares (50.000 m^2), this results in a requirement of 250.000 L/day. Taking into account the estimated values for the efficiency of fog collectors in the analysed area (between 4 and 7 L/m^2/day, on average 5.5 L/m^2/day), a 40 m^2 panel can collect between 160 and 280 litters daily (average 220 L/day).

To ensure an additional flow of at least 12.500 L/day (representing a minimum contribution of 5% of the total daily requirement), it is proposed to install 80 collectors, each with an area of 40 m^2 (4 m wide and 10 m high), i.e., a collection area of 3.200 m^2. The distance between collectors, both parallel and in line, is 5 m. This space allows for adequate air and fog flow, easy access for maintenance, and structural stability (for anchoring and tensioning).

Taking all this data into account, the total area occupied on the ground by the entire collector system will be approximately 0.5 ha, which can be integrated into the areas adjacent to the plot or on sloping, low-yield land. Figure 7 shows a model layout of fog collectors on the slope of an uncultivated hill.

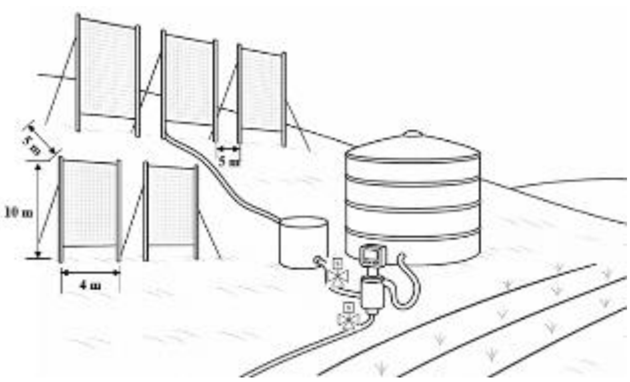

Fig. 7. *Example of fog collector layout on a hill*

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The collectors will provide a daily contribution of an estimated flow rate between:

- 12.800 L/day (at a minimum yield of 4 L/m^2/day);
- 22.400 L/day (at a maximum yield of 7 L/m^2/day).

This amount of water is equivalent to covering 5.1% to 9% of daily needs, thus reducing the pressure on the irrigation network during dry periods. The supply obtained can fully cover the water needs for 0.6 - 1.1 ha of the total soil, reducing water stress during critical periods of plant development.

3.2.2. Estimated implementation costs

The total estimated cost for one collector (purchase + transport + anchoring) is between 400 EUR and 600 EUR, depending on the materials used and the complexity of the installation [12]. For the 80 units proposed:

- Total cost of the collectors: between 32000 EUR and 48000 EUR;
- Additional infrastructure costs are estimated as follows:
  - o Connection pipes and gutters: 2500 EUR;
  - o Semi-buried tank (capacity 100 m^3): 2000 EUR;
  - o Labour and installation work: 6000 EUR.

Therefore, the total cost of the pilot project is estimated at 42500 EUR and 58500 EUR, or approximately 530-730 EUR per collector unit installed (including infrastructure).

Even though the initial investment is quite high for a complementary solution, it is offset by savings in water consumption from conventional sources, reduced water stress, and increased productivity in drip-irrigated plots. Furthermore, the lack of operating costs (the collectors are passive) and the high durability of the equipment (over 10 years) result in medium-term amortization (estimated at 4 – 5 years) if the system is correctly integrated into an intensive production chain.

4. Conclusions

The pilot project for the use of fog collectors as a complementary water source, applicable to a 5-hectare plot with a value-added crop, is an additional proposal for improving the irrigation system. The gravity-fed system, with 40 m^2 vertical panels arranged on a slope and connected to a collection tank, was designed using actual flow and cost calculations and has been shown to provide a significant portion of the water needed for drip irrigation during dry periods, thus reducing dependence on conventional sources.

This article demonstrated that the modernisation of irrigation systems is not only feasible but necessary. The combination of precision technologies with digitization and alternative water sources offers a sustainable solution for adapting agriculture to new climatic conditions. The proposed model can serve as a basis for the regional expansion of smart irrigation systems, contributing both to the resilience of agricultural production and to the sustainable conservation of water resources.

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