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Beyond water stress: Exploring the wastewater-irrigation nexus for sustainable Agriculture

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Abstract

Water management is one of the crucial factors that impact the operation of agriculture globally. As droughts become more frequent due to global warming, the management of this limited resource becomes increasingly important. Lately, the potential utilization of wastewater for irrigation purposes is considered a game changer, overlooking that in many cases, wastewater treatment is poorly studied. This work aimed to examine the EU member states water management practices based on the FAO database. The Kruskal-Wallis test of the clustered countries revealed that the developing regions pay the most attention to wastewater treatment within the EU. Even though the most developed countries treat quite low amount of wastewater, and based on previous studies they are more likely to face water scarcity, the applied methods did not reveal any difference between the water stress levels of the clustered member states. The run of the statistical tests highlighted that the various water stress levels of the examined countries could not be connected with the utilization of the existing irrigation systems. Based on these results, increasing the application of the built-out system may in many cases be sufficient to serve and even increase the operation of the agricultural production without putting additional strain on the resources in the short term. However, the development of wastewater-based irrigation systems could be useful in those regions where the utilization of the existing irrigation system is already high, or face elevated water stress. Since we are still learning how to deal with this new resource, the farm-scale utilization of less contaminated water sources like collected rainwater or greywater could facilitate the development of the new system. This promising approach could not only contribute significantly to several Sustainable Development Goals but also has the potential to enhance and over time even supersede the current method.

Keywords

Water,
Wastewater,
Irrigation,
Agriculture,
Sustainability

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Highlights for public administration, management and planning:

- The research analyzes water management practices across the European Union member states using FAO's Aquastat database.
- The study found that developing EU regions pay more attention to wastewater treatment compared to more developed regions, which treat a lower amount of wastewater despite facing water scarcity risks.
- The EU countries' diverse water stress levels could not be attributed to the use of the current irrigation system. In short term, the built-out system can often satisfy the demand of the agricultural production without increasing significantly the pressure on the limited resources.
- The wastewater-based innovations should utilize less contaminated water sources like collected rainwater or greywater in more water-stressed areas to facilitate the development of a new sustainable irrigation system.

1 Introduction

Agriculture plays a pivotal role in achieving several Sustainable Development Goals (SDGs), serving as a linchpin among others for global food security and environmental sustainability. However, the water-intensive nature of agriculture raises concerns about the efficient utilization of resources, especially water. Lately, the frequent droughts caused by global warming have led to more focus on water management (Vicente-Serrano et al. 2020; Muñoz et al. 2020; Wu et al. 2022). In agriculture, the irrigation tariffs can differ significantly between countries and even across regions (Pereira & Cunha Marques 2020) for to this reason, various alternatives have been developed to solve the irrigation issue. Theoretical suggestions, like the formulation of water tariffs, are often studied (Portoghese et al. 2021; Pinto et al. 2021; Pronti & Berbel 2023), but technological ideas, like the hybrid application of photovoltaic, battery, and diesel set-up (Haffaf et al. 2021) which reduce irrigation costs and CO2 emissions, could also be found. Lately, the utilization of wastewater for irrigation purposes seems to be a game changer in agriculture and sustainable development too (Al Hamedi et al. 2023; Moussaoui et al. 2023).

While studies can more easily measure the ecological consequences of wastewater irrigation, such as soil salinity or heavy metal buildup (Singh 2021), evaluating public acceptance of this alternative is somewhat more complex. According Fielding et al. (2019), public acceptance can be influenced by numerous social factors. However, it seems that education and limited contact with recycled water have the greatest potential to broaden acceptance. Considering that 38% of the EU population, and 29 % of EU territory were affected by water scarcity in 2019, causing annual droughts cost of 2 to 9 billion euro (European Commission 2024), the European Union also recognized the wastewater's potential and introduced a new regulation (EU 2020/741) in May 2020. It defines the Minimum Quality Requirements (MQR) of treated wastewater, which makes it possible to use it for watering crops too. However, it does not explicitly write about the quantity of wastewater that needs to be treated (Regulation 2020), and neither mentions any suggestions to mitigate the difficulties related to irrigation water pricing (Hellegers & Davidson 2023). Beyond the technological and economic dimensions, there is a growing recognition of the need for integrated water governance approaches. It involves a comprehensive understanding of policy frameworks, stakeholder engagement, and transboundary water agreements, particularly in regions where water sources are shared between countries (Islam & Repella 2015). The concept of water diplomacy is gaining prominence as a critical tool to address water-related conflicts and enhance cooperation in regions facing scarcity. By creating synergies between national and international actors, water diplomacy aims to balance competing demands for water resources in agriculture, industry, and domestic use (Krzymowski 2021). In the European Union, transboundary water cooperation plays a significant role, especially in areas where rivers or water bodies are shared by multiple countries, such as the Danube River basin (Klimes et al. 2019). Incorporating these governance perspectives into wastewater management could ensure more equitable and sustainable water distribution, addressing both local needs and broader regional challenges. The current work aimed to study the wastewater management practices within the member states of the European Union. However, the research does not only shed light on international differences but also analyses the current use of water-based controlled irrigation systems. The study also strives to develop and present a theoretical framework that could significantly improve sustainable agricultural operations through a novel approach to wastewater management, while contributing to ecological, environmental, and social sustainability.

2 Materials and methods

To analyze the context of water management and sustainable agriculture, an extensive database was needed consisting of relevant variables from both fields. The local statistical offices frequently apply their own methods to estimate various values. For this reason, international organizations' databases were reviewed to find the most comprehensive one for this purpose, though this strongly limited the availability of variables. Thus, the main source of the dataset used became the FAO Aquastat database (AQUASTAT 2024). The involved data and the applied statistical tests are presented in Fig. 1.

Considering the limited accessibility of the information, only the 28 member states of the European Union - including the UK, which spent more time in the EU than out of it within the studied timeframe - were analyzed between 2016 and 2020. The starting point was defined by the date when the SDGs entered into force (2016), while the endpoint was the latest available year (2020). The quantity of data

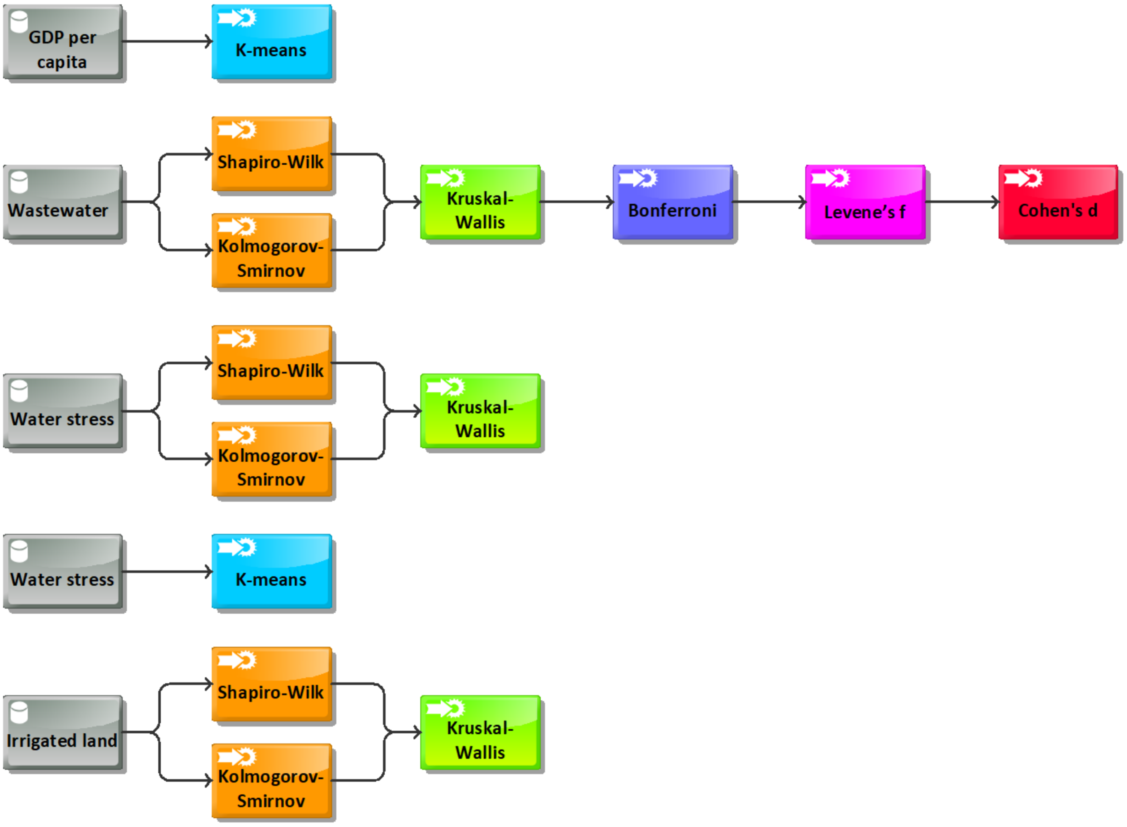

Fig. 1 The stages of data processing

and the length of the studied interval are limited, but the current dataset is still suitable for revealing complex relations and directions. The used variables are presented in Table 1.

The K-means clustering method is one of the most widely used classification techniques (MacQueen 1967). In the current work, it was used to classify the studied countries into three groups (low-income, middle-income, and high-income) based on their GDP per capita. This approach starts the procedure with an initial clustering where each data point is assigned to its closest cluster center. However, this starting classification may not be ideal (Ahmed et al. 2020). The K-mean method updates the cluster centers by taking the average of the points currently assigned to them, and repeating the process of reclassification and center update until certain convergence criteria are met, such as a predefined number of iterations or a minimal change in the clustering pattern (Jin & Han 2011; Na et al. 2010).

To compare group means, a two-sample t-test could be used. However, in this case, three clusters were studied, which required the application of One-Way Analysis of Variance (ANOVA). It is considered the extended version of the two-sample t-test (GUVEN 2022). ANOVA requests the normality of the dataset, which was studied by the Shapiro-Wilk, and Kolmogorov-Smirnov tests. The former is a non-parametric test, so it is not sensitive to any specific distribution. Its value is determined by the sample mean, standard deviation, and standardized residuals (Khatun 2021). The other method is also a non-parametric test for normal distribution. It is calculated by comparing the cumulative distribution function of the sample to that of a normal distribution (Demir 2022). As both of the tests rejected the normal distribution of the dataset, one of the ANOVA's preconditions was not fulfilled, so this test could not be used. The Kruskal-Wallis test (H) is the nonparametric alternative of one-way ANOVA. The nonparametric tests generally have lower statistical power compared to parametric tests, meaning they may be less likely to detect significant differences between groups when they exist. While the Kruskal-Wallis test provides insight into differences among groups, interpreting the results can be challenging, particularly when dealing with large, heterogeneous datasets. However, this method is ideal for comparing the medians of two or more independent samples, without requiring a normal distribution of the dataset. The

Table 1 The relevant variables of the database

Variable	**Description**	**Unit**
GDP per capita	The total gross value added by resident producers in the economy, along with any product taxes not considered in the output valuation, divided by the mid-year population (The World Bank 2024).	current US$ /inhabitant
Treated municipal wastewater	The amount of municipal wastewater that was processed, cleaned, and transformed and can be safely reintroduced to the environment or the water cycle, minimizing environmental impact (Nizamuddin et al. 2019).	10^9 m^3/year
Water stress	The percentage of water withdrawn by all major sectors compared to the total amount of renewable freshwater available, while taking into account environmental water needs (FAO 2018).	%
Irrigated land	The share of the area equipped for full control irrigation is actually irrigated (FAO 2018).	%

data is combined and assigned ranks (1 being smallest, N being largest) (Lüpsen 2023). Ranks within each group are then summed, and a probability is calculated by the following equation;

$$H = \frac{12}{NN+1} \sum \frac{R_i^2}{n_i} - 3N + 1 \qquad (1)$$

N stands for the total number of data involved, n_i represents the number of individuals in each group (where i indicates the group number), R_i symbolizes the combined rank scores for all data within each group (Hoffman 2019).

The Bonferroni adjustment post hoc test was needed to identify potential dissimilarities between the studied clusters. This post hoc test was chosen since it rejects the false null hypothesis with the lowest probability. However, if differences are found, their extents could not be defined by this test (Lee & Lee 2018). To determine these values Cohen's d test could be applied. It measures the magnitude of the difference between two groups, allowing the quantification of the contrast in their characteristics (Gignac & Szodorai 2016). To analyze the homogeneity of variances Levene's test had to be used (Hosken et al. 2018). This method was needed for the definition of the ideal form of Cohen's d test.

3 Results and discussion

The structure of analysis follows the work of Liao et al. (2021) who studied the wastewater management practices of Asian countries, which also provides a great comparison for the current findings. At first, K-means clustering was used to define the studied countries' level of development, based on their GDP per capita. This statistical method specified low-income, middle-income, and high-income clusters. To compare how the amount of treated municipal wastewater differs according to the clusters, one-way ANOVA was planned to be used. However, during the analysis of preconditions, the Shapiro-Wilk, and Kolmogorov-Smirnov tests rejected the normality of the dataset. Due to this reason, the Kruskal-Wallis test had to be used. This test was considered because it is not sensitive to differences in variance. The run of the Kruskal-Wallis test rejected the null hypothesis, so there is a significant difference between the studied cases.

The box plots in Fig. 2 highlight the distinctive approach to wastewater treatment in countries with the highest GDP per capita. They had the lowest amount of treated wastewater, while the middle-income countries paid the most attention to it. Since the Kruskal-Wallis test itself did not reveal which cases differed, the Bonferroni post hoc test was applied to outline the contrast within the groups. Its results are presented in Table 2.

Table 2 Differences related to the treatment of municipal wastewater

Sample 1 - Sample 2	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig.**	**Adj. Sig.**
high-income - low-income	−17.967	13.988	−1.284	0.199	0.597
high-income - middle-income	53.576	14.449	3.708	0.000	0.001
low-income - middle-income	35.610	7.066	5.040	0.000	0.000

The analysis highlighted the statistically significant differences between the high-income and middle-income, in addition to the low-income and middle-income clusters. However, the post hoc test was not able to provide information about the magnitude of these differences. To solve this shortcoming, Cohen's d for Two-Sample with Unequal SD was applied, since the run of Levene's test

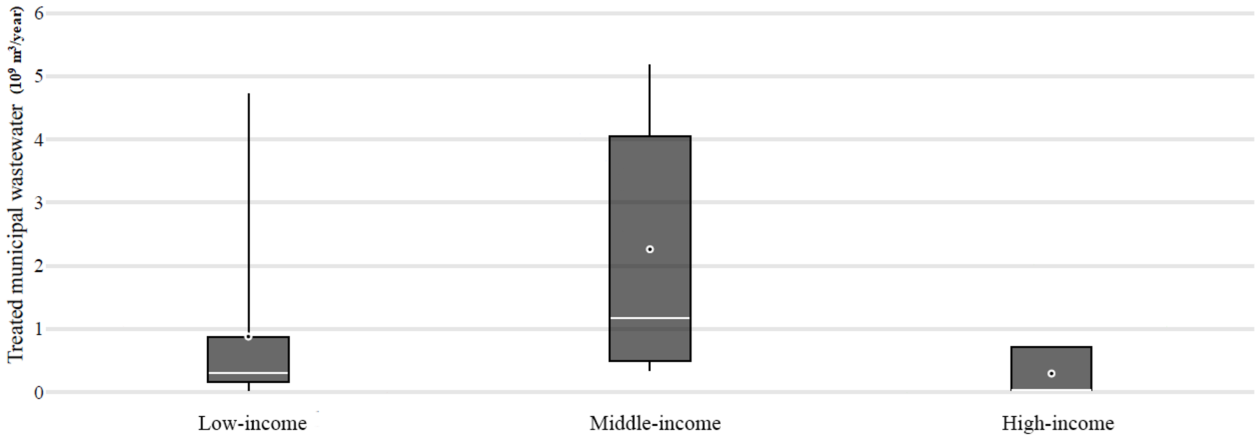

Fig. 2 The distribution of the treated wastewater across the studied groups

revealed that the samples are not homogenous. The standardized difference between the means of the middle-income and high-income clusters was negligible, while the Cohen's d value for the middle-income and low-income countries was moderate.

These findings contrast with the results of the Asian studies. The work of Liao et al. (2021), highlighted, that the countries with high GDP per capita such as UAE or Singapore treat high levels of wastewater, and the somewhat less wealthy countries like Japan and Korea treat less wastewater. Within the studied Asian countries the less developed nations like the Philippines and Pakistan paid the least attention to this activity.

The current study's outcomes could be interpreted as a sign of exposure to water stress in countries with high GDP per capita. The findings of Shaikh et al. (2022) also suggest that wealthier countries contribute significantly to water stress. Based on these assumptions the high-income countries should face higher water stress. To test this hypothesis one-way ANOVA should be run. However, the Kolmogorov-Smirnov and the Shapiro-Wilk test indicated the data is significantly different from a normal distribution. So Kruskal-Wallis test was applied, which did not show any differences between the clusters. This could be caused by the relatively low level of water stress within the sample. As seen in Fig. 3, most of the countries belonged to the low to slight water-stressed area.

This outcome could be aligned with the study of Doeffinger & Hall (2020), who emphasized a negative trend in water stress, especially in the case of Western and Eastern European countries.

These observations and the rejection of the previous hypothesis could suggest the high utilization rate of the fully controlled irrigation system. This way these countries could decrease their water needs in agriculture and through this the level of water stress. To analyze this hypothesis K-means clustering was used to classify the involved countries into three groups according to their water stress level. Based on Shapiro-Wilk, and Kolmogorov-Smirnov tests, the run of the Kruskal-Wallis test was needed to study the assumption. However, the test's outcome did not support the hypothesis, since it did not reveal significant differences across the samples. Even though the Mediterranean countries face the most water stress within the European Union (Ungureanu et al. 2020), based on the FAO's data – presented in Fig. 4 – the application of built-out fully controlled irrigation systems is not fully exploited even in these countries (except Malta). Policymakers should encourage its exploitation through regulations that reduce economic barriers, such as tariffs and taxes on irrigation systems. According to the studied dataset, each member state has a high level of irrigation system coverage, which could not obstacle the increased utilization of it, not like the previously mentioned factors (Berbel et al. 2019; Sa'diyah et al. 2021). In addition, water scarcity tends to be not connected to the application of the existing system.

The application of wastewater for agricultural purposes has been a topic for a long time and it truly has the potential to reshape this sector. The studied European countries also showed great opportunities for the development of wastewater treatment, and the application of treated wastewater for irrigation purposes seems to be a game changer in the near future. However, the inadequately treated wastewater led to the accumulation of heavy metals and harmful substances in soil and plants (Panhwar et al. 2022; Xu et al. 2022). Additionally, it elevated pathogen levels and heightened microbial risks to the well-being of humans and an-

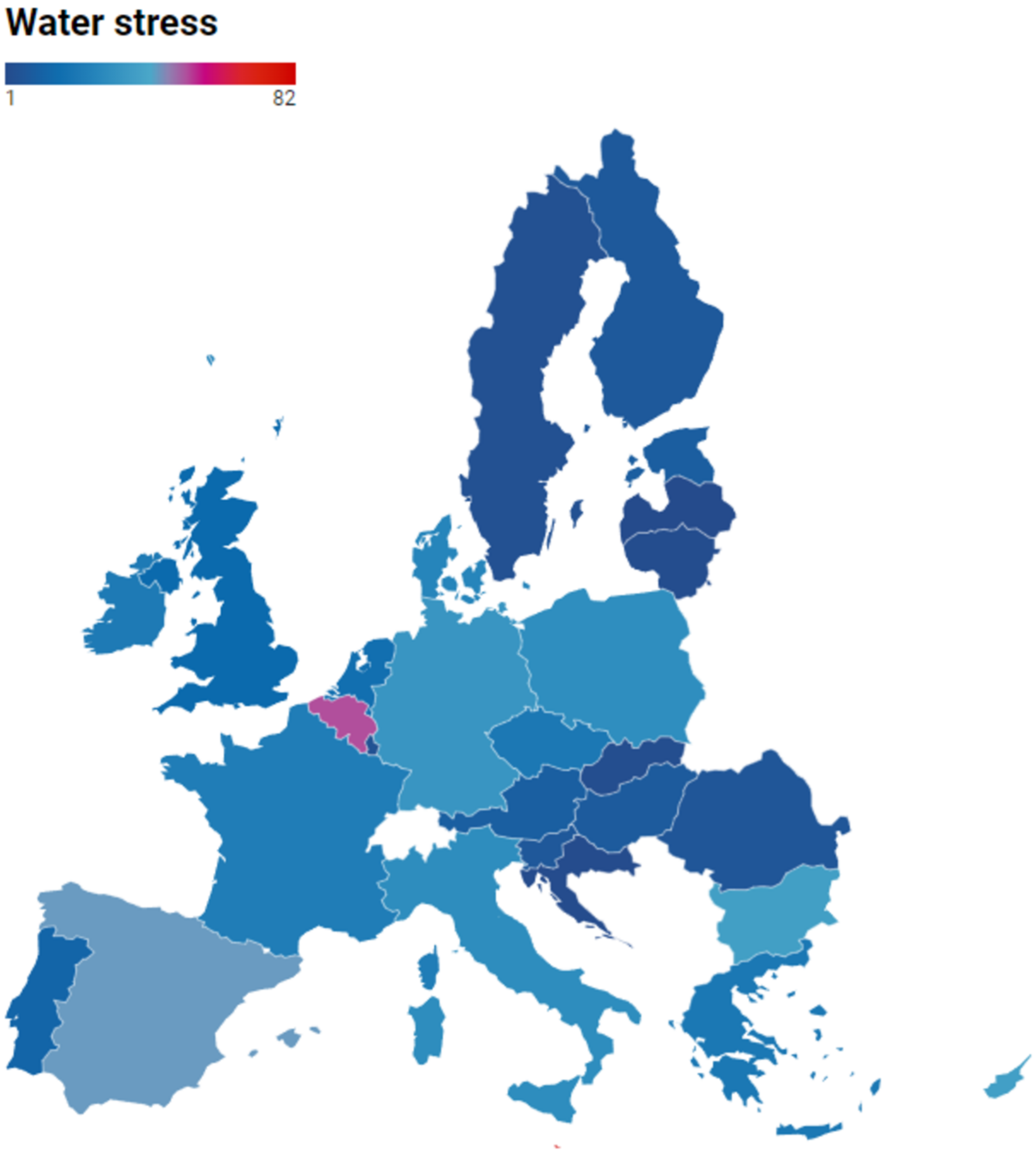

Fig. 3 The water stress level (%) of the studied countries in 2020 Note: Malta had the highest water stress, but due to the small size of the island it is hardly visible (own elaboration, 2024, based on Aquastat 2024)

imals (Singh 2021; Tariq 2021). Even though often greywater is considered "light wastewater" – since it doesn't contain toilet waste and has lower levels of germs (Khajvand et al. 2022) – and the collected rainwater stands even further from the "classical wastewater", they are less contaminated than blackwater (Raimondi et al. 2023; Morales-Figueroa et al. 2023). It makes their treatment easier and the filtered water quality higher, and more secure (Liu et al. 2021; Xu et al. 2023; Awasthi et al. 2024). In this case, the proper procedure is also essential, where more steps could be separated. The development of membrane filtration systems, such as reverse osmosis, ultrafiltration, and nanofiltration (Joseph et al. 2023; Gupta et al. 2024; Zhao et al. 2025), provides highly efficient wastewater treatment by removing contaminants, pathogens, and even micro-pollutants. The application of Internet of Things (IoT) sensors can be deployed in wastewater treatment plants too, among others to monitor water quality, water flow, pH levels, or contaminant concentrations in real time (Narayanan et al. 2023; Venkateswaran et al. 2023). Lately, after the last "official" section

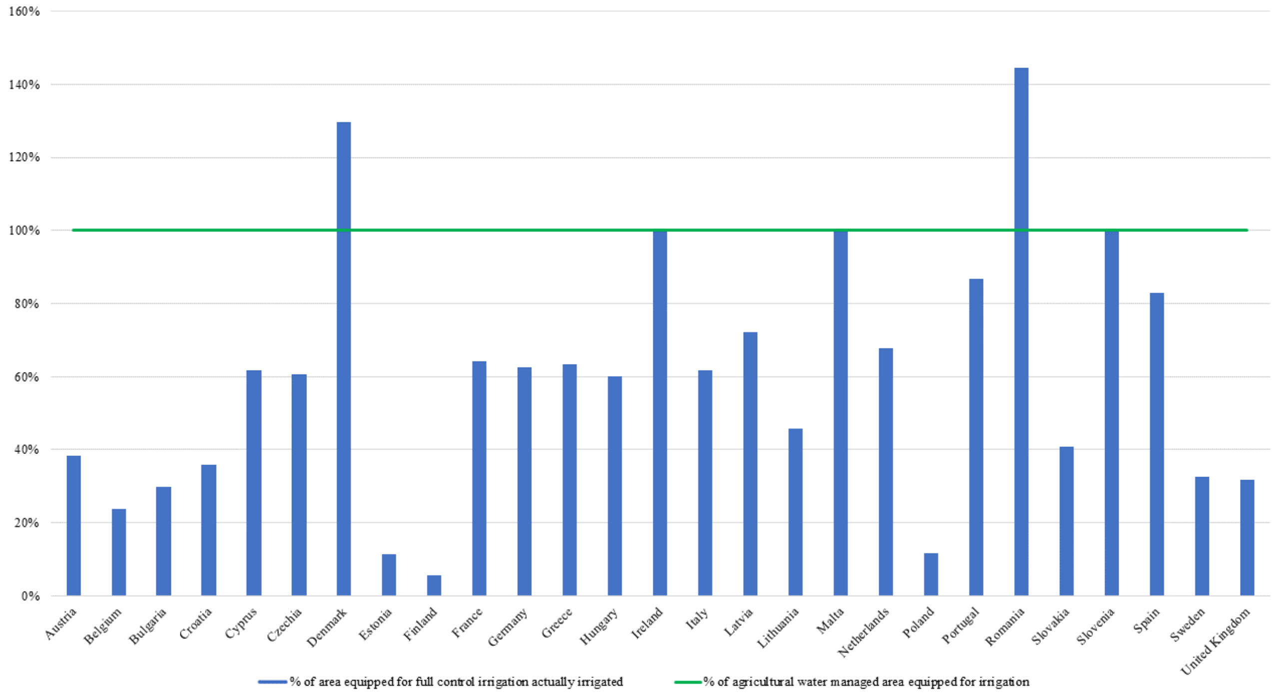

Fig. 4 Share of area equipped for full control irrigation actually irrigated within the EU members in 2020 (own elaboration, 2024 based on Aquastat 2024); Note: some of the data are estimated by FAO

the possible application of natural filtering methods is studied (Chaieb et al. 2023). These various plant and insect-based solutions could further eliminate the residues by breaking them down into non-harmful substances while creating new habitats, green spaces, and resources (Chen et al. 2023; Enns et al. 2023). The construction of wetlands for treating wastewater is advantageous. It has the ability to remove emerging organic contaminants (EOCs) and antibiotic-resistant bacteria (ARB), which are increasingly prevalent in wastewater (Christofilopoulos et al. 2019). The combination of fungi and microalgae to treat wastewater is also a beneficial organic method. Fungi are capable of degrading a wide range of organic pollutants and absorbing heavy metals. When combined with microalgae, fungi can create a synergistic effect, enhancing their ability to treat wastewater and produce valuable products which can be recovered and used for other applications (Leng et al. 2021). The treated wastewater could also be piped through small hydroelectric power plants to the irrigation area (Baran 2021), thus mitigating the costs of implementation and irrigation. A possible framework for a sustainable solution to exploit the potential of this resource is presented in Fig. 5.

This approach could address several important problems at once. However, the time and costs related to the planning and construction would hinder the fast execution of a such system. Promoting research into low-cost, natural filtering methods (e.g., plant and insect-based solutions) could lead to more affordable irrigation systems. The future implementation of the presented theoretical framework should ideally be studied at the farm or community level. As the latest studies reveal, the current state of wastewater-based irrigation is not developed enough (even on small scale) (Truchado et al. 2021; Moreno-Mesonero et al. 2022; Oliveira et al. 2023).

Governments could incentivize the exploration of wastewater reuse in agriculture through subsidies, tax breaks, or grants for farms that develop their own infrastructure. While the treatment of collected rainwater is often skipped - even though it is also needed - filtering greywater still seems to be less resource-intensive than filtering blackwater (Khanam & Patidar 2022; Rivadulla et al. 2024; Zheng & Deng 2024). In addition to these, the guidelines for the implementation of standardized Water Reuse Risk Management Plans are still not widely accessible, which could hamper the widespread of know-how (Jiménez-Benítez et al. 2020; Radini et al. 2023). Policymakers should work to develop and disseminate clear guidelines and best practices, establishing

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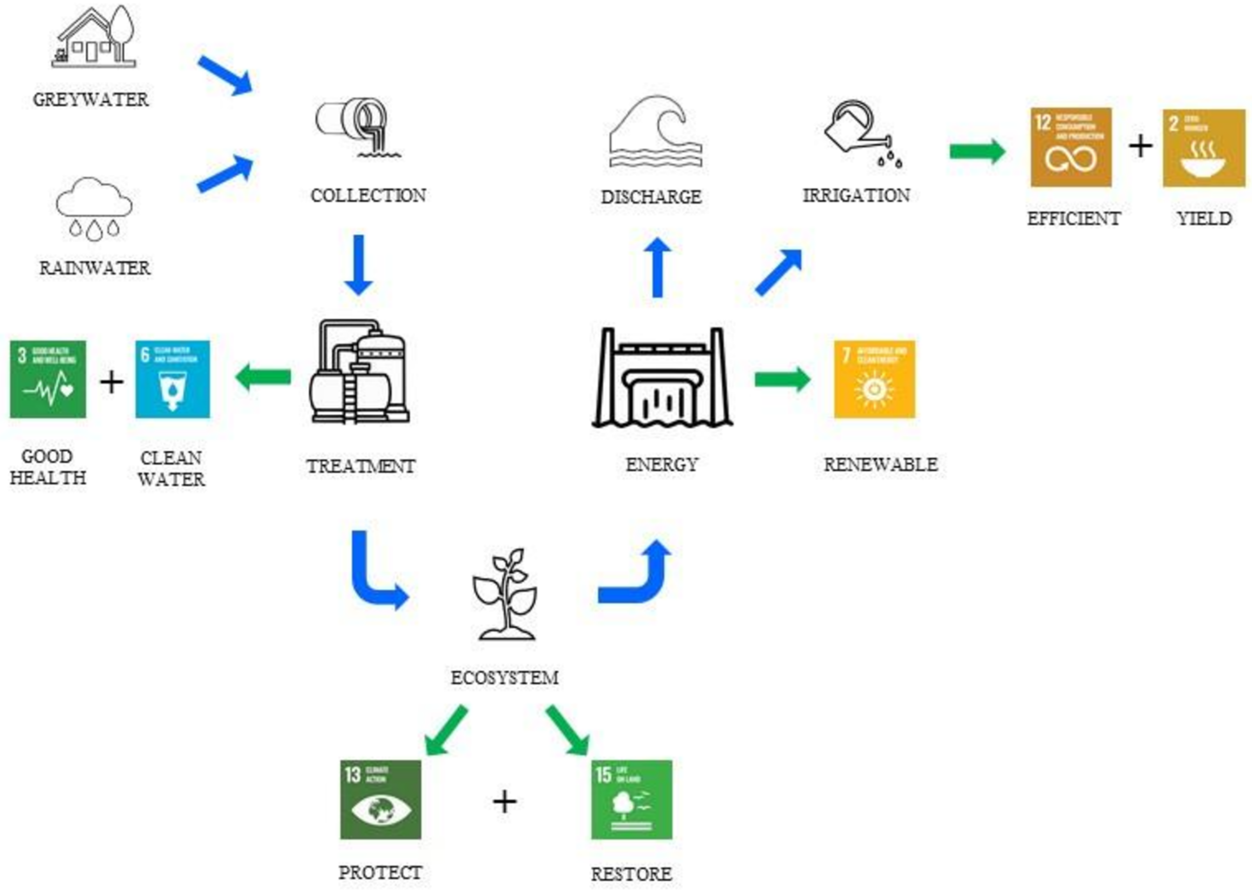

Fig. 5 A theoretical framework for a wastewater-based sustainable irrigation system

a legal framework for monitoring and controlling the quality of treated wastewater. While the southern countries (Cyprus, France, Greece, Italy, Portugal and Spain) already had comprehensive application and regulation for the reuse of treated wastewater (McLennan et al. 2024), the lack of harmony among the existing standards could have created trade barriers across Europe for agricultural goods irrigated with reclaimed water (Drewes et al. 2017). The new standards clearly define four categories of reclaimed water for agricultural irrigation based on E. coli, BOD5, and TSS levels, and they also specify crop categories that can be irrigated with these water types (McLennan et al. 2024).

4 Conclusion

Sustainable agriculture is critical; its efficient operation can provide multiple advantages to related fields through improvement. While irrigation is a vital practice in farm management, its high water consumption raises concerns about its efficiency. Lately, the potential rise of wastewater-based irrigation systems receives more attention, although often the wastewater management practices themselves are not well-known. The middle-income EU countries seem to be more attentive regarding wastewater treatment than the high-income nations. However, only a few member states should consider water scarcity as a driving force of water-related development. The operation of wastewater-based irrigation systems is also supported by EU policy, but the secure application of this new resource remains far from ideal. On a small scale, using grey or collected rainwater, the suggested approach could be more viable than the blackwater-based alternative, especially in areas where the current system is heavily utilized. However, as long as the utilization of fully controllable irrigation systems remains unexploited despite their widespread availability, installing a new system may not be beneficial for farmers. Regulating irrigation tariffs at an international level could also contribute significantly to increasing agricultural efficiency in the short term. At the same time, the feasibility and acceptance of the theoretical framework should be studied as the next stage of current research, since in the long term, the wastewater-based irrigation system could expand and even replace the current one.

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