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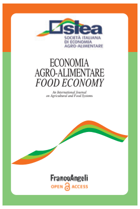

Irrigation reuse of urban treated wastewater: A qualitative analysis to support crop production in Campania

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Abstract

The sustainability of the agricultural sector is closely linked to the ability of territorial system to effectively address the challenges of water resource management in the context of climate change.
The reuse of treated wastewater is increasingly recognized as a key strategy for ensuring a sustainable water supply in agriculture.
This study proposes an innovative methodological approach aimed at identifying the Utilised Agricultural Area (UAA) potentially irrigable with treated wastewater, with particular attention to high value crops certified as Protected Designation of Origin (PDO) and Protected Geographical Indication (PGI) in the Campania region.
The methodology is based on the integration of data from three main sources: National Information System for Water Management in Agriculture (SIGRIAN) for mapping irrigated areas; European Environmental Agency (EEA) database linked with National Information System for the Protection of Italian Waters (SINTAI) for classifying wastewater treatment plants; and Italian Agricultural Payments Agency (AGEA) for identifying land use in irrigated areas. This approach enables the association, in accordance with Water Reuse Regulation (EU) 2020/741, of the water quality class required for each crop

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with that one potentially available from wastewater treatment plants, also taking into account the existence of suitable distribution infrastructures.
The results of the analysis highlight that the proposed methodology, applied to agricultural sector in Campania, with a focus on high-quality production, can effectively guide public policies in promoting targeted infrastructure investments. These investments aim to protect areas most vulnerable to drought and support high value crops, particularly certified ones, through the adoption of advanced technological solutions and integrated water resource planning, which are key to ensuring the resilience and long-term prosperity of the regional agricultural sector.

Introduction

In recent decades, access to water resources has become increasingly challenging due to environmental, climatic, and human pressures (Scanlon *et al.*, 2023). Agriculture, highly dependent on water and a major driver of its quality and quantity, is among the most vulnerable sectors (Ingrao *et al.*, 2023). According to the EEA, about 20% of Europe's territory and 30% of its population face water stress, with droughts causing annual economic losses of up to €9 billion, excluding ecosystem damage (EEA, 2020, 2021). Southern Europe and the Mediterranean, already characterized by limited and irregular water availability – especially in summer – are expected to face worsening conditions due to climate change. The EEA projects up to a 40% reduction in summer river discharge in southern and southwestern Europe under a 3°C warming scenario (EEA, 2021). Rising temperatures, changing precipitation patterns, and more frequent extreme weather events are reducing crop yields and altering crop distribution, severely impacting agricultural production and infrastructure (EEA, 2020).

Sustainable freshwater management is essential for Sustainable Development Goals (SDG), as emphasized by UN SDG 6 (Clean Water and Sanitation) and its links to SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land) (United Nations, 2015, 2016). In Europe, the Water Framework Directive (WFD) has regulated water quality since 2000, aiming to ensure high standards for freshwater resources. More recently, the European Green Deal, thanks to a package of strategies[1], has prioritized

1. *In primis* the Biodiversity Strategy for 2030, the European Climate Law, the Farm to Fork Strategy, and the recently-adopted Nature Restoration Regulation, among others.

sustainable and resilient water management as key to achieving climate neutrality by 2050 (Koundouri *et al.*, 2024).

Climate change is expected to increase irrigation needs by 20% (EEA, 2021), adding pressure on agriculture, which must produce more with fewer inputs to meet growing food demand. In this context, treated wastewater reuse is increasingly viewed as a viable alternative water source for irrigation in several EU countries (Blanco-Gutiérrez & *et al.*, 2021; Hamam *et al.*, 2024; McLennan *et al.*, 2024). Across Europe, WasteWater Treatment Plants (WWTPs) capable of producing water for reuse are mainly located in coastal and southern areas, as well as densely populated northern regions. Treated wastewater is primarily used for agricultural purposes, as well as for urban and industrial uses. Agriculture accounts for about 25% of freshwater withdrawals in Europe (Farabegoli, 2023; United Nations, 2017).

The EU has actively promoted treated wastewater reuse in agriculture, especially in water-stressed areas, culminating in the Water Reuse Regulation (WRR (EU) 2020/741) (Ramm *et al.*, 2024). This regulation sets minimum quality standards for reuse in irrigation, protecting human and animal health and the environment (Hamam *et al.*, 2024). It aligns with the European Green Deal and the Circular Economy Action Plan (Berbel *et al.*, 2023; Maffettone *et al.*, 2024).

Reuse potential depends on technological factors (e.g., advanced WWTPs), agronomic factors (crop type, irrigation methods), and managerial aspects – particularly the presence of infrastructure and entities responsible for distributing reclaimed water. Reuse is most effective where well-structured irrigation services and networks already exist, reducing the need for new distribution investments (Drei *et al.*, 2025).

Following the WRR (EU) 2020/741, Italy is updating national legislation with a new Presidential Decree to extend reuse provisions beyond the EU regulation, including industrial wastewater reuse (with exceptions) and additional uses (Farabegoli, 2023).

Given the WRR (EU) 2020/741's recent introduction, scientific literature on treated wastewater reuse under these new rules is limited, especially regarding actual or potential use for crops (Hamam *et al.*, 2024).

Several studies have analyzed, from a technical and economic perspective, the potential of reusing treated urban wastewater to meet irrigation needs (Birol *et al.*, 2010; Mancuso *et al.*, 2022; Ventura *et al.*, 2019). However, such research has generally focused on the quantitative aspect, both for treated wastewater and irrigation requirements, often neglecting the crop context, which is instead a crucial element in effective reuse planning.

In this regard, this study proposes a methodology to investigate the potential for wastewater reuse in irrigation, employing a qualitative approach that integrates agronomic, technological, and managerial factors in assessing reuse potential. This research was developed within SMACC project, funded by Ministry of Agriculture, Food Sovereignty and Forests (MASAF) under Development and Cohesion Fund. This innovative approach allows overcoming the traditional focus solely on quantitative aspects, providing a more comprehensive and realistic view of the opportunities and challenges associated with the sustainable management of wastewater in agriculture. As a case study, the methodology is applied in Campania, a region in southern Italy with diversified and high-value farming, but with limited research on water reuse.

The paper is structured as follows: first, an overview of Campania's agriculture, water resources, climate change, irrigation, and high-value crop production; second, a description of methods combining datasets on irrigation areas, WWTPs, and crops; finally, a presentation and discussion of results focusing on wastewater reuse potential for agricultural irrigation, particularly for high-value crops.

1. Agricultural and irrigation context in the Campania region

Campania, in southern Italy, features a Mediterranean climate with dry summers and mild, rainy winters (Burak and Margat, 2016; Mendicino *et al.*, 2008). Precipitation varies from 800 mm on the coast to 2,000 mm in mountainous areas (Busico *et al.*, 2017). The region's climatic attributes, coupled with its considerable morphological diversity, encompassing fertile coastal plains, hilly terrains, and mountainous landscapes, have historically facilitated the proliferation of intensive agriculture, marked by a high degree of crop diversification.

Indeed, agriculture in Campania is distinguished by the cultivation of esteemed crops, including PDO and PGI products, which are intricately connected to local traditions and the region's identity. Cereals, vegetables, and citrus fruits comprise more than 85% of the overall agricultural output in the Mediterranean region, although crops like olives and grapes represent a substantial portion of the agricultural production (Leff *et al.*, 2004).

The region produces iconic products, including San Marzano tomatoes, Annurca apples, and wines with the Controlled Designation of Origin (DOC) designation. Such crops require high-quality irrigation water, with strict limits on pollutants to ensure food safety and environmental sustainability.

The official statistics demonstrate the significant value of crops, including many with PDO and PGI labels, as an essential component of the regional agricultural economy. With 63 PDO and PGI certified foods and wines, a value of 896 million Euros according to the Ismea-Qualivita Observatory, the agri-food production and the wine sector account respectively for 88.5% and 11.5% of the entire sector (Fondazione Qualivita, 2025).

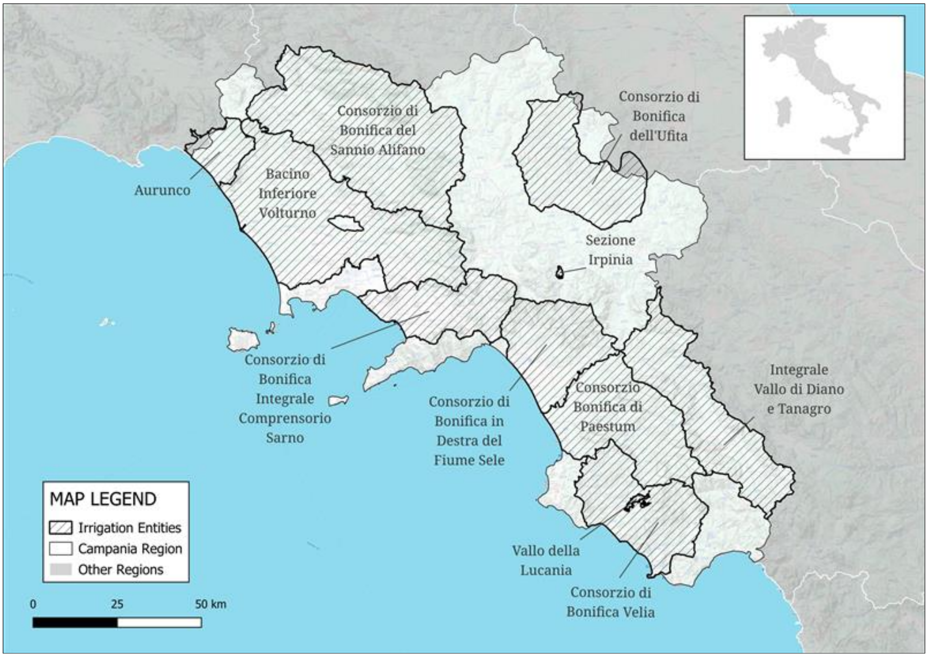
Agriculture in Campania is heavily dependent on irrigation, making it particularly vulnerable to climate change and increasing droughts, especially in the Piana del Sele and Cilento areas. Groundwater overuse and surface water pollution further exacerbate water scarcity (Cusano *et al*., 2019; Mastrocicco *et al*., 2021).

The irrigation of high-value crops needs high-quality water, which imposes strict limitations on salinity, sodium, heavy metals, nitrates, and microbiological pollutants to ensure production quality, food safety, and soil sustainability (Bordbar *et al*., 2025), preserve soil structure and yields (Ayers and Westcot, 1985), avoiding environmental and health hazards (Paranychianakis *et al*., 2015; Pedrero *et al*., 2010).

Despite having the highest water availability in the Southern Apennine River Basin, Campania transfers significant volumes to neighboring regions, resulting in inter-regional dependencies. The irrigation system relies on a combination of surface watercourses (e.g., Volturno, Sele) and aquifers, which are managed by 11 irrigation consortia across the region.

The management of the irrigation network in the Campania region is currently delegated to 11 irrigation entities (Figure 1).

Figure 1 - Maps of irrigation entities in the Campania region



Source: SIGRIAN, 2025.

Irrigation and reclamation consortia in Campania operate across approximately 100,000 hectares, serving regional agricultural enterprises. The territory is divided into irrigation districts based on water availability and distribution schemes, which define irrigated areas and guide strategic planning.

These consortia manage about 67% of the region and oversee 70% of irrigated land through public systems, underscoring the strategic role of irrigation in the regional economy.

Despite favourable conditions, agriculture in Campania faces growing challenges related to climate change, water scarcity, and aging infrastructure. Ensuring the sector's resilience requires not only the sustainable use of existing water resources but also the development of alternative, reliable sources (Colella *et al.*, 2021).

Improving water-use efficiency and promoting reuse solutions are essential to protect agricultural productivity, food security, and environmental sustainability (Braca *et al.*, 2019).

2. Materials and methods

The WRR (EU) 2020/741 establishes minimum quality requirements for the use of treated wastewater in agriculture, based on a site-specific risk management plan. These requirements are determined by comparing the treatment level achieved at the WWTP (resulting in a water quality class from A to D) with the quality required for target crops and irrigation systems (Joint Research Centre, 2017; 2022).

The WRR (EU) 2020/741 defines four water quality classes (A, B, C, D), linked to both crop categories and irrigation methods (Figure 2). It authorizes the reuse of treated municipal wastewater for three crop groups:

- food crops consumed raw;
- processed food crops (post-harvest treatment required);
- non-food crops.

The regulation also introduces indicative treatment requirements:

- Class A: secondary treatment, filtration, and disinfection;
- Classes B, C, D: secondary treatment and disinfection.

The quality class can be adjusted using accredited additional barriers, such as specific irrigation methods that reduce crop exposure to pests. However, the actual classification depends on microbiological parameters, not only on the treatment applied (Figure 3).

Figure 2 - Classes of reclaimed water quality and permitted agricultural use and irrigation method

Minimum reclaimed water quality class	**Crop category (*)**	**Irrigation method**
A	All food crops consumed raw where the edible part is in direct contact with reclaimed water and root crops consumed raw	All irrigation methods
B	Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals	All irrigation methods
C	Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals	Drip irrigation (**) or other irrigation method that avoids direct contact with the edible part of the crop
D	Industrial, energy and seeded crops	All irrigation methods (***)

(*) If the same type of irrigated crop falls under multiple categories of Table 1, the requirements of the most stringent category shall apply.
(**) Drip irrigation (also called trickle irrigation) is a micro-irrigation system capable of delivering water drops or tiny streams to the plants and involves dripping water onto the soil or directly under its surface at very low rates (2-20 litres/hour) from a system of small-diameter plastic pipes fitted with outlets called emitters or drippers.
(***) In the case of irrigation methods that imitate rain, special attention should be paid to the protection of the health of workers or bystanders. For this purpose, appropriate preventive measures shall be applied.

Source: WRR (EU) 2020/741.

Figure 3 - Reclaimed water quality requirements for agricultural irrigation

Reclaimed water quality class	**Indicative technology target**	**Quality requirements**				
		E. coli (number/ 100 ml)	**BOD_5 (mg/l)**	**TSS (mg/l)**	**Turbidity (NTU)**	**Other**
A	Secondary treatment, filtration, and disinfection	≤ 10	≤ 10	≤ 10	≤ 5	*Legionella* spp.: < 1,000 cfu/l where there is a risk of aerosolisation Intestinal nematodes (helminth eggs): ≤ 1 egg/l for irrigation of pastures or forage
B	Secondary treatment, and disinfection	≤ 100	In accordance with Directive 91/271/ EEC (Annex I, Table 1)	In accordance with Directive 91/271/ EEC (Annex I, Table 1)	–	
C	Secondary treatment, and disinfection	≤ 1,000			–	
D	Secondary treatment, and disinfection	≤ 10,000			–	

Source: WRR (EU) 2020/741.

The innovative element of the WRR (EU) 2020/741 is its fit-for-purpose approach – moving away from the precautionary "one-size-fits-all" model to a system based on risk assessment and proportionality, balancing safety with feasibility[2].

Data collection

To assess the reuse potential of treated wastewater in Campania, geospatial and technical data from three domains were integrated as shown in Table 1:

Table 1 - Data collection

Framework	**Parameter**	**Database**	**File format**	**Reference year**
Managerial	Irrigation area	SIGRIAN	Shapefile	2025
Technical	WWTP locations and treatments	EEA/SINTAI	Shapefile/excel	2020
Agronomic	Crop data	AGEA	Shapefile	2018

Source: Authors' elaboration.

2. Cf. the European Commission's Communication *"Guidelines to support the application of Regulation 2020/741 on minimum requirements for water reuse"* (2022/C 298/01).

Given the exploratory nature of this study, the use of data from different years was deemed appropriate, as the primary objective was to propose and test a methodological framework for qualitative and spatial investigation rather than to produce temporally consistent estimates.

WebGIS SIGRIAN

SIGRIAN is the reference database for the irrigation sector. It is a Geographic Information System managed by CREA PB and realized in collaboration with the irrigation and reclamation consortia and the Regions. It contains geographic and alphanumeric spatial data concerning irrigation features in collective irrigation areas: administrative boundaries, irrigated and irrigable areas, irrigation supply, hydrographic network, crop type, and climatic characteristics (Zucaro *et al.*, 2019). For the purposes of the analysis, the perimeter to date of the irrigation areas considered as the territorial reference unit for the survey was extracted from the SIGRIAN database.

EEA/SINTAI database

The European Environmental Agency database[3], in connection with SINTAI[4], contains the information transmitted by the Member States every two years, in compliance with Art. 15 of the Urban Wastewater Treatment Directive 91/271/EEC (UWWTD). In this way, the European Commission verifies the progress made by Member States in the field of purification and collection by periodically requesting information on agglomerations of 2,000 population equivalents (P.E.)[5] or more.

Among the information (available in Excel and shapefile format), the following were used for this survey:

- *geographical location of the wastewater treatment plants:* latitude and longitude;
- *technical characteristics:* presence of primary, secondary, advanced treatment, disinfection, and filtration (required in Table 2 of the WRR);
- *activity status:* inactive, active, temporarily inactive;
- *design and incoming organic capacity.*

3. The European Environment Agency (EEA) is a European Union (EU) agency that provides independent information on the environment. Its primary role is to help the EU and its member and cooperating countries make informed decisions to improve the environment, integrate environmental considerations into economic policies, and support a sustainable transition.

4. SINTAI is the National Information System for the Protection of Italian Waters managed by ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale) open source which allows access, management and consultation of environmental information.

5. Which means the organic biodegradable load having a five-day biochemical oxygen demand (BOD5) of 60 g of oxygen per day.

The data used refers to the year 2020, as submitted in 2022 by MS. This data does not vary significantly from year to year.

AGEA Graphical Cultivation Plan

The Graphical Cultivation Plan (GCP), managed by AGEA, graphically represents a farm's crops on a given territory with detailed information. The GCP, related to the year 2018 and in shapefile format, was processed using Geographic Information System (GIS) software. The georeferencing of each plot allowed for the agronomic framing of the area under study. Area-based CAP aid recipients compile the data, so they do not cover the entire national agricultural area, although they have a high degree of coverage. However, their potential lies in classifying each plot of land in such detail as to characterize each crop also with respect to its mode of consumption, allowing it to be linked to the crop categories envisaged by the WRR (EU) 2020/741.

For the purposes of the survey, the following parameters were used, relating to:

- *Land occupation (codi_occu)*: this identifies both specific vegetation cover and the absence of crops (e.g., durum wheat or set-aside land);
- *Use (codi_use)*: allows the indication of the prevalent use of a specific land occupation (e.g., Industry or canteen);
- *Use (codi_usage)*: identifies specific cultivation methods or specific information related to the land occupation (e.g., pot cultivation or rough grazing);
- *Quality (codi_qual)*: provides specifications on the indicated land occupancy (e.g., Early or Late).

Spatial analysis

To integrate previous quantitative analysis (Ferrigno *et al.*, 2023), this study adopts a qualitative approach to investigate the implementation of Regulation (EU) 2020/741 on wastewater reuse. Emphasis is placed on developing a spatially explicit method to assess qualitative compliance between supply and demand, addressing a research gap in the existing literature where such methodological integration remains limited.

Using GIS (QGIS and ArcGIS Pro), a geodatabase was created by overlaying:

1. SIGRIAN irrigated areas. The reference territorial units for the survey are the irrigation areas as currently registered in SIGRIAN. An irrigation area is a physical-administrative unit served fully or partially by an irrigation infrastructure system, identifying lands subject to irrigation. Managed by an irrigation authority, these areas are potentially connected to a water

distribution network. This characteristic was considered a key enabling factor for promoting wastewater reuse;
2. WWTPs with adequate treatment levels. WWTPs in the study area were classified based on the technological objectives outlined in Table 2 of the WRR (EU) 2020/741, allowing identification of plants potentially producing reclaimed water of quality classes A, B, C, or D. This classification is theoretical, as actual quality depends not only on treatment level but also on microbiological parameters, which were not considered here due to incomplete or unavailable data. Such parameters are better assessed through direct sampling for water-reuse risk management plans. Only WWTPs with an incoming load of ≥ 2,000 P.E. were included, excluding smaller plants, due to factors affecting technical and economic feasibility, such as treatment line completeness and water production capacity;
3. Crop types and their respective water quality requirements. All crops listed in the AGEA 2018 GCP were compiled into an Excel file to categorize them according to the WRR (EU) 2020/741 crop categories, which are groups based on reclaimed water quality requirements. This classification followed the provisions of Table 2 (Figure 4) and Table 4.2 (Figure 5) from the document *Guidelines to support the application of the WRR on minimum requirements for water reuse* which further specifies reclaimed water quality classes according to crop type and intended use.

Only agricultural plots were retained; non-agricultural land was excluded. All crops were analysed as potentially irrigable in an extreme shortage scenario. Each crop was associated with its minimum required water quality class, solely based on crop type, thus excluding mitigation barriers such as irrigation methods, as defined in Article 3(12) of the WRR (EU) 2020/741.

A specific focus was given to high-value PDO/PGI crops of Campania (e.g., Melannurca Campana PGI, Pomodoro San Marzano PDO). By intersecting crop layers with the official production areas defined in their specifications, it was possible to highlight branded plots that could potentially benefit from reclaimed water.

While the presence of a crop within a PDO/PGI area does not guarantee its branding status, for the purpose of this analysis, these areas were considered as proxies for high-value production.

Figure 4 - Suggested number of barriers needed for irrigation with reclaimed water, according to their quality

Category (1)	**Irrigation of vegetables consumed raw (2)**	**Irrigation of vegetables after processing and pastures (3)**	**Irrigation of food crops other than vegetables (orchards, vineyards) and horticulture (4)**	**Irrigation of fodder and seeded crops (5)**	**Irrigation of industrial and energy crops (6)**
A	0	0	0	0	0
B	1	0	0	0	0
C	3	1	1	0	0
D	forbidden	forbidden	3	1 (*)	0

The following definitions for each column in the table are in line with Table 1 of Annex 1 to the Water Reuse Regulation and are intended to help the reader find the crop category that broadly corresponds to the ISO categorisation, and thus identify which additional barriers may be needed:

(1) Minimum reclaimed water quality class.
(2) Food crops consumed raw where the edible part is in direct contact with reclaimed water and root crops consumed raw.
(3) Processed food crops and non-food crops, including crops used to feed milk- or meat-producing animals.
(4) Food crops consumed raw, where the edible part is produced above ground and it is not in direct contact with reclaimed water.
(5) Food crops consumed raw, where the edible part is produced above ground and is not in direct contact with reclaimed water; processed food crops, and non-food crops, including crops used to feed milk- or meat- producing animals (in both cases, when drip irrigation or another irrigation method is used that avoids direct contact with the edible part of the crop). NB. The seeded crops mentioned here can be seeds for human consumption or for use as animal fodder.
(6) Industrial, energy crops, and seeded crops (intended to produce seeds for sowing).

(*) Note from ISO 16075:2020: Edible seeds or seeds for sowing which have been irrigated for less than 30 days prior to harvesting. If the period before harvesting is equal to or higher than 30 days, then class D can be directly applicable without restrictions (i.e. without the need for additional barriers).

Source: WRR (EU) 2020/741. Guidelines to support the application of WRR (EU) 2020/741on minimum requirements for water reuse (2022/C 298/01).

Figure 5 - Examples on how to calculate number and types of barriers based on type of crop and required reclaimed water quality classes

Crop category (Annex 1 Table 1 of the Regulation) (1)	Example crops (Table A.1 ISO 16075-2:2020)	Reclaimed water quality class (Annex 1 Table 1 of the Regulation)	Number of required barriers (Table 3 ISO 16075-2:2020 (3) = Table 2 of this Notice)	Possible accredited barriers (Table A.1 ISO 16075-2:2020 and Table 2 ISO 16075-2:2020 (4) = Table 3 of this Notice)	Number of barriers (Table 2 ISO 16075-2:2020 = Table 3 of this Notice)	Note
All food crops consumed raw, where the edible part is in direct contact with reclaimed water, and root crops consumed raw	Leafy crops grown on the soil surface are eaten raw (e.g., lettuce, spinach, Asian cabbage, cabbage, celery). Food crops ingested raw, which grow above ground, and the edible portion is <25 cm above the soil surface (e.g., pepper, tomato, cucumber, courgettes, young beans).	A	0	–	0	–
		B	1	Sun-resistant cover sheet OR Additional disinfection in field (low level)	1	–
		C	3	High-level disinfection + Sun-resistant cover sheet	2+1	–
				Subsurface drip irrigation, where water does not ascend by capillary action to the ground surface + Sun-resistant cover sheet*	3 (+1)	* Sun-resistant cover sheet is an extra barrier to prevent contact by the capillary action of drip irrigation. –
		D	Forbidden*	–	–	* In accordance with Table 3 ISO16075: 2020 and NOTE 3 of Table a.1: Effluents of medium quality (D) should not be used for the irrigation of vegetables.
	Food crops that can be ingested raw, which grow in the soil (e.g. carrot, radish, onion)	A	0	–	–	–
		B	1	Low level disinfection	1	–
		C	3	No combination of accredited barriers seems to be possible	–	–

Source: Guidelines to support the application of Regulation 2020/741 on minimum requirements for water reuse (2022/C 298/01).

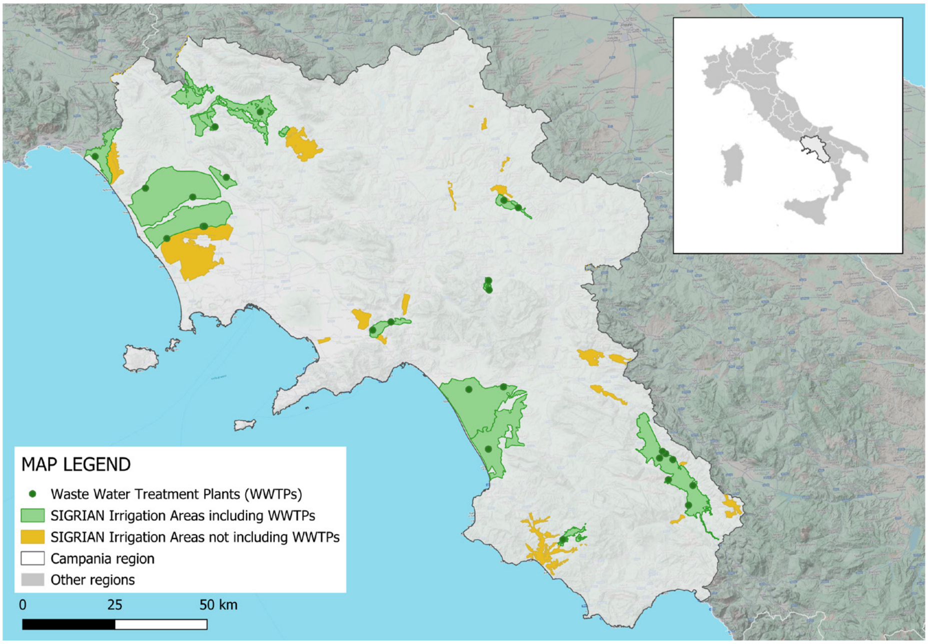
3. Results

The analysis relies on cross-sectional data from different years (SIGRIAN 2025, EEA/SINTAI 2020, AGEA 2018). Therefore, even if some of the data analyzed are unlikely to vary from year to year, the results provide a static snapshot of potential reuse, rather than actual or time-varying capacity. They should be read as indicative of spatial opportunities and constraints.

3.1. *Characterisation of the study area*

The Campania region comprises 40 irrigation areas, managed by 11 separate irrigation authorities. 12 areas contain at least one WWTP (Figure 6 and Table 2), totalling 26 WWTPs. All selected WWTPs can potentially produce class B, C, or D reclaimed water, indicating that additional treatment is required for crops that require class A water.

Figure 6 - Map of WWTPs included in irrigated areas in the Campania region



Source: Authors' elaboration.

Table 2 - List of WWTPs included in irrigation areas and their potential quality class according to the treatment applied

Reclamation and irrigation consortia	**Irrigation Areas (ID Sigrian)**	**Irrigation Areas (SIGRIAN name)**	**WWTP (ID EEA)**	**WWTP (EEA name)**	**Potential quality reclaimed water**
Bacino Inferiore Volturno	4160	Aurunco	IT15Q90000003455	Cellole Impianto di Baia Domizia Borgo Centore	BCD
	4946	DX-VOLTURNO	IT15Q90000003445	Vitulazio Impianto di Selva Via Fontana Pigna	BCD
			IT15Q90000003453	Falciano del Massico Impianto del Capoluogo Localita Casale	BCD
			IT15Q90000003464	Grazzanise Depuratore Comunale	BCD
	4947	SX-VOLTURNO	IT15Q15000000007	Villa Literno Ce Impianto Foce Regi Lagni	BCD
			IT15Q90000003454	Cellole Depuratore Localita Doccia	BCD
			IT15Q90000003563	Rotondi Impianto di Rotondi Via Patricelli	BCD
Paestum	4171	Paestum	IT15Q90000003617	Capaccio Sa Impiantovarolato	BCD
Sarno	4155	Paludi	IT15Q90000003628	Mercato S. Severino Frazione Costa Impianto Mercato S. Severino	BCD
			IT15Q90000003631	Nocera Superiore Impianto Comprensiorale	null
Sannio Alifano	4476	Sannio Alifano	IT15Q90000003439	Alife Impianto di Fusaro Vadolargo	BCD
			IT15Q90000003456	Pietramelara Depuratore Comunale	BCD
Ufita	4163	Ufita B	IT15Q90000003587	Frigento Impianto Frigento Localita Pila ai Piani	BCD
	4179	Macchioni	IT15Q90000003603	Sturno Impianto di Sturno	BCD
Destra del Fiume Sele	4164	Destra Sele	IT15Q90000003623	Battipaglia Sa Impianto Tavernola	BCD
			IT15Q90000003625	Eboli Sa Impianto Macchioncello	BCD
Reclamation and irrigation consortia	4144	Montella, Cassano, Montem	IT15Q11000000000	Montella Impianto di Montella Loc Ta Bagno Stratola	BCD
			IT15Q90000003571	Montella Impianto di Montella	BCD
Vallo di Diano e Tanagro	4165	VALLO DI DIANO E TANAGRO	IT15Q90000003634	Montesano Marcellana Buonabitacolo Impianto Capoluogo Peschiera	BCD
			IT15Q90000003636	Sala Consilina Impianto Localita Taverne	BCD

			IT15Q90000003637	Sala Consilina Impianto Loc Macchia dell'Aspide	BCD
			IT15Q90000003638	Sala Consilina Impianto Loc San Giovanni	BCD
			IT15Q90000003644	Teggiano Depuratore di Teggiano	BCD
			IT15Q90000003684	Padula Impianto del Capoluogo	BCD
			IT15Q90000003704	Sassano Impianto Via Limiti	BCD
Vallo della Lucania	4487	Vallo	IT15Q90000003477	Vallo Della Lucania Impianto Localita Ischitella	BCD

Source: Authors' elaboration.

From an agronomic point of view, the study area is characterized by a total UAA of 53.638,70 hectares, made up of about 70% by the ten prevailing crop types shown in Table 3.

Table 3 - Prevalent crop types in the Campania region

CROP	**UAA (ha)**	**UAA (%)**
Meadow	6.819,38	12,71
Mais	5.278,47	9,84
Arable land	5.229,49	9,75
Tomato	5.186,93	9,67
Oats	4.844,84	9,03
Ryegrass	4.786,64	8,92
Hazel	2.055,07	3,83
Strawberry	1.401,44	2,61
Alfalfa	1.296,96	2,42
Sulla	1.034,39	1,93
SubTotal	**37.933,61**	**70,72**
Other crops	15.705,09	29,3
Total	**53.638,70**	**100,0**

Source: Authors' elaboration.

Crop types have been categorized into 12 categories according to the WRR (EU) 2020/741 and its accompanying guidance document. As it turns out, about 94% of the UAA can be attributed to five crop categories (Table 4).

Table 4 - Crop categories as per WRR (EU) 2020/741 of the survey area (in order of occurrence)

Crop category Reg 741/2020 (WRR)	**UAA (ha)**	**UAA (%)**
Fodder crops for feed for milk- or meat-producing animals (e.g., alfalfa)	20.709,37	38,6
Food crops grown above ground where the edible portion is <25 cm above the soil surface, eaten cooked or processed (e.g., aubergine, pumpkin, green beans, artichoke)	9.593,78	17,9
Industrial, energy crops, and seeded crops (intended to produce seeds for sowing)	7.808,47	14,6
Food crops that grow above ground, such as > 50 cm or more above the ground with edible skin (orchard for fruits with edible skin: apple, plum, pear, peach, apricot, persimmon, cherry, citrus fruits, dates; or orchard for fruits eaten after peeling: mango, avocado, papaya, pomegranate). Orchard for fruits eaten after processing (e.g., olives)	7.440,34	13,9
Leafy crops grown on the soil surface are eaten raw (e.g., lettuce, spinach, Asian cabbage, cabbage, celery). Food crops ingested raw, which grow above ground and the edible portion is <25 cm above the soil surface (e.g., pepper, tomato, cucumber, courgettes, young beans).	4.824,34	9,0
Subtotal	**50376,3**	**94,0**
Other crop category	3.262,40	6,1
Total	**53.638,70**	**100,0**

Source: Authors' elaboration.

Table 5 represents the UAA and the corresponding percentages for each water class in the Campania region. The preponderant part, more than 60%, is made up of crops for which at least one water class B is required.

Table 5 - Minimum class of reclaimed water required in hectares and % of UAA

Required water class	UAA (ha)	UAA (%)
A	4.968,04	9,3
B	32.932,26	61,4
C	7.440,34	13,9
D	8.298,06	15,5
Total	**53.638,70**	**100,0**

Source: Author's elaboration.

Having defined the qualitative supply and demand in the study area, it is possible to correlate the two pieces of information to define the potential for reuse.

3.2. *Reuse potential*

By correlating the potential quality of treated wastewater with the minimum water quality requirements of different crops, the reuse potential of treated wastewater in the study area can be assessed from multiple perspectives.

The first area-based approach identifies zones where the water supply falls short of demand, highlighting vulnerable areas for targeted interventions to boost irrigation from alternative sources.

The first, area-based approach, examines which crops would be most affected under extreme drought due to their high-quality water needs, revealing specific agricultural vulnerabilities and resilience. However, this method overlooks the spatial distribution of crops, which may be fragmented and served by different treatment plants.

To overcome this, a third, mixed approach, combines both area-based and crop-based analyses, focusing on specific zones or crop types – such as PDO and PGI products – allowing a more detailed and nuanced assessment.

Area-based approach

Table 6 presents the analysis results from the irrigation area perspective. Over 70% of the UAA considered in the study is potentially irrigable with treated wastewater. In areas served by at least one WWTP, the potentially irrigable UAA exceeds 90%, except for the Destra Sele irrigation area, where only 60% of the area is potentially irrigable. The remaining area consists of crops requiring Class A water, which could be irrigated after WWTP upgrades and/or the implementation of suitable additional barriers at the supply point.

This approach provides a valuable tool for strategic infrastructure planning and helps identify priority WWTPs for reuse investments, as outlined in Art. 5 of Ministerial Decree 185/2023 and the forthcoming Presidential Decree.

Table 6 - Assessment of the irrigation potential of any WWTPs included in the irrigation areas

Irrigations area	**UAA (ha)**	**WWTP (n° - potential class quality water)**	**UAA potential irrigable (%)**	**UAA no irrigable (%)**
Montella, Cassano, Montemarano	138,47	2 BCD	96,9	3,1
Paludi	45,86	BCD, null*	93,0	7,0
Aurunco	1.239,92	BCD	95,5	4,5
Ufita B	619,10	BCD	98,0	2,0
Destra Sele	8.308,38	2 BCD	60,9	39,1
Vallo di Diano e Tanagro	2.646,71	7 BCD	98,4	1,6
Paestum	5.133,13	BCD	92,6	7,4
Macchioni	223,41	BCD	97,6	2,4
Sannio Alifano	7.127,66	2 BCD	99,7	0,3
Vallo	249,14	BCD	99,4	0,6
Dx-Volturno	10.611,90	3 BCD	97,7	2,4
Sx-Volturno	5.578,81	3 BCD	97,4	2,6
28 remaining irrigations area	11.716,21	None	0,00	100,0
Total	**53.638,70**		**70,4**	**29,6**

* WWTPs that do not have the minimum level of treatment required by European regulations to produce water that can be reused for irrigation purposes.

Source: Authors' elaboration.

Crop-based approach

By applying the analysis to individual crops or categories, Table 4 can be expanded into Table 7, which distinguishes UAA located in irrigation areas including a WWTPs from those without available reclaimed water classes in it (n.d.), highlighting the potentially irrigable share.

For example, 93,42% of "nut trees", which require Class B water, are potentially irrigable as they lie within irrigation areas including a WWTPs producing Class B water.

The most disadvantaged category is "Industrial, energy, and seed crops for sowing – non-food nursery", which requires only Class D water, yet only 52,78% of their UAA is in irrigation areas, including WWTPs.

The analysis also shows that crops needing Class A water are currently not irrigable with reclaimed wastewater anywhere in the study area, as no WWTP produces this water quality class.

Table 7 - Distribution of crop categories in relation to the presence of WWTPs and the quality class produced by it. Evaluation of irrigation potential with reclaimed water

Crop category Reg 741/2020	Total UAA (ha)	Required water class	Class of water available	SAU (ha)	Irrigable UAA	Irrigable UAA (%)
Orchard for nuts (e.g., almonds, pistachios)	869,15	B	BCD	811,97	YES	93,42
		B	n.d.	57,19	NO	
Food crops that grow above ground, such as > 50 cm or more above the ground with edible skin (orchard for fruits with edible skin: apple, plum, pear, peach, apricot, persimmon, cherry, citrus fruits, dates; or orchard for fruits eaten after peeling: mango, avocado, papaya, pomegranate). Orchard for fruits eaten after processing (e.g., olives)	7.440,34	C	BCD	5.042,58	YES	67,77
		C	n.d.	2.397,76	NO	
Food crops that can be ingested raw, which grow in the soil (e.g., carrot, radish, onion)	143,70	A	BCD	83,28	NO	–
		A	n.d.	60,42	NO	
Food crops grown above ground that can be eaten after drying and cooking (dry beans, lentils)	72,05	B	BCD	48,42	YES	67,20
		B	n.d.	23,63	NO	
Food crops grown above ground where the edible portion is <25 cm above the soil surface, eaten cooked or processed (e.g., aubergine, pumpkin, green beans, artichoke)	9.593,78	B	BCD	6.612,75	YES	68,93
		B	n.d.	2.981,03	NO	
Food crops grown on the soil that can be eaten raw after peeling (e.g., watermelon, melon, pea)	1.486,25	B	BCD	1.392,46	YES	93,69
		B	n.d.	93,79	NO	

Food crops eaten cooked that grow in the soil (e.g., potato)	201,65	B	BCD	125,92	YES	62,44
		B	n.d.	75,73	NO	
Fodder crops for feed for milk- or meat-producing animals (e.g., alfalfa)	20.709,37	B	BCD	17.123,68	YES	82,69
		B	n.d.	3.585,69	NO	
Industrial, energy crops, and seeded crops (intended to produce seeds for sowing – no food plant nursery)	462,36	D	BCD	244,03	YES	52,78
		D	n.d.	218,33	NO	
Industrial, energy crops, and seeded crops (intended to produce seeds for sowing – food plant nursery)	27,22	D	BCD	22,72	YES	83,46
		D	n.d.	4,50	NO	
Leafy crops grown on the soil surface are eaten raw (e.g., lettuce, spinach, Asian cabbage, cabbage, celery). Food crops ingested raw, which grow above ground and the edible portion is <25 cm above the soil surface (e.g., pepper, tomato, cucumber, courgettes, young beans)	4.824,34	A	BCD	4.081,47	NO	
		A	n.d.	742,87	NO	
Industrial, energy crops, and seeded crops (intended to produce seeds for sowing)	7.808,47	D	BCD	6.333,21	YES	81,11
		D	n.d.	1.475,26	NO	
Total	**53.638,70**			**53.638,70**		**70,39**

Source: Authors' elaboration.

Mixed approach to the PDO and PGI case study

Specifically, PDO and PGI products in the fruit and vegetable sector were analyzed, assuming that all the crops within the municipal boundaries defined in the production regulations for each product are certified production. Results show that while over 70% of the regional UAA is potentially irrigable (Table 6), this drops to 42% for the branded crops examined (Table 9).

Only Carciofo di Paestum PGI and Nocciola di Giffoni PGI have their entire UAA irrigable. Conversely, Cavolfiore della Piana del Sele PGI, Cipollotto Nocerino PDO, and Rucola della Piana del Sele PGI cannot be irrigated without adopting risk-reduction measures, as the supplying WWTPs do not produce the required Class A water.

Ciliegia di Bracigliano PGI and Melannurca Campana PGI can be partially irrigated with reclaimed water, limited to UAA portions within irrigation areas served by WWTPs. Similarly, Pomodoro San Marzano dell'Agro Sarnese-Nocerino PDO irrigation depends on water quality class – Class A for fresh consumption and Class B for industrial use.

Table 9 - Campania high value crops from and irrigation potential with reclaimed water

Campania's high-value crops	Irrigations area	Class of water available	Class of water required	UAA (ha)	Potential irrigation	Irrigable UAA (%)
ARTICHOKE	Destra Sele	BCD	B	67,83	YES	
	Paestum	BCD	B	75,12	YES	
Total				**142,95**		**100,00**
CAULIFLOWER	Destra Sele	BCD	A	109,08	NO	
	Paestum	BCD	A	23,24	NO	
Total				**132,32**		**0,00**
CHERRY TREE	Labso		C	0,73	NO	
	Paludi	BCD	C	2,86	YES	
	S. Anna - S. Lucia		C	0,29	NO	
Total				**3,88**		**73,63**
ONION, INCLUDING LONG-TYPE VARIETIES (ECHALION)	Paludi	BCD	A	2,63	NO	
Total				**2,63**		**0,00**
APPLE TREE	Sannio Alifano	BCD	C	35,27	YES	
	Valle telesina		C	2,65	NO	
	SX-REGI LAGNI		C	31,09	NO	
	DX-VOLTURNO	BCD	C	117,04	YES	
	SX-VOLTURNO	BCD	C	6,21	SI	
Total				**192,26**		**82,45**
HAZELNUT TREE	Paludi	BCD	B	0,33	YES	
Total				**0,33**		**100,00**
TOMATO (San Marzano)	Labso		A	1,94	NO	
			B	0,22	NO	
	Sarno - S. Valentino - S.		A	1,23	NO	
	Paludi	BCD	A	0,22	NO	
		BCD	B	0,63	YES	
	Bottano		A	0,10	NO	
Total				**4,34**		**14,60**
ROCKET	Destra Sele	BCD	A	186,36	NO	
	Paestum	BCD	A	61,10	NO	
Total				**247,46**		**0,00**
Total Region				**726,18**		**42,04**

Source: Authors' elaboration.

A significant issue arises regarding the availability of treated wastewater for irrigating Campania's PDO and PGI crops. Many of these high-value crops are partially or entirely excluded from reuse irrigation due to the lack of required water quality or adequate distribution infrastructure. This limitation poses a serious challenge, especially in extreme drought conditions, given the economic and strategic importance of these productions for the region.

In 2023, Melannurca Campana PGI generated €11.5 million in turnover (€2.1 million from exports), followed by Pomodoro San Marzano dell'Agro Sarnese-Nocerino PDO (€8.5 million) and Rucola della Piana del Sele PGI (€2.1 million) (ISMEA & Fondazione Qualivita, 2023).

This gap between economic value and access to alternative water sources highlights the urgent need for targeted infrastructure improvements and protective measures to ensure the sector's resilience and competitiveness amid growing water scarcity.

4. Discussion and conclusions

Water scarcity, combined with the growing and constant demand for water in agriculture, is expected to increase the need for non-conventional water sources, particularly reclaimed wastewater. The regulated and monitored use of treated wastewater helps preserve freshwater resources, alleviates pressure on natural reserves, and strengthens the resilience of agricultural systems. From a purely quantitative point of view, full recycling of wastewater would cover between 38% and 53% of what is needed for Italian irrigation (Fondazione Utilitatis, 2024). This estimate doesn't consider qualitative aspect.

In line with the provisions of the WRR (EU) 2020/741 focused on water quality standards, the methodology proposed in this study – applied to the Campania region – seeks to establish a transferable and replicable framework for linking the quality classes required by different crops with those supplied by WWTPs . The integration of multiple datasets enabled the identification of areas currently unsuitable due to either insufficient water quality or the lack of appropriate distribution infrastructure.

The focus on high-value crops offers a valuable tool for strategic infrastructure planning, targeting both increased agricultural resilience and the protection of PDO and PGI-certified products, which are central to the identity and agri-food economy of Campania and Italy. Crop failure in such contexts not only results in yield loss but also carries significant economic consequences related to quality certifications and brand reputation. In these cases, where produce is often consumed fresh and unprocessed, the main challenge lies in meeting strict requirements for irrigation water quality – either through investments in WWTPs or by adopting multi-barrier approaches at the supply point.

To date, the few Regions that have identified in their Water protection plans the WWTPs already intended for reuse, need to be updated in accordance with the new regulatory provisions (SNPA – Sistema nazionale protezione ambiente, 2024).

To support this process, methodologies such as the one presented here are essential for identifying current limitations in reuse practices and guiding targeted investment strategies.

The results highlight two key areas for improvement: (1) the capacity of treatment plants to produce water of sufficiently high quality, and (2) the availability of an operational distribution network – such as irrigation consortia or water management entities – that can coordinate reuse across existing infrastructures or, at minimum, manage supply efficiently. This type of assessment is fundamental for determining the technical and economic feasibility of agricultural water reuse, as it considers the entire reuse chain – from production and storage to distribution and field application – at both national and regional scales.

The upgrade of WWTPs is a priority for the reuse (Fondazione Utilitatis, 2024) also addressed by Italian National Recovery and Resilience Plan. Investments on irrigation networks for the distribution of treated urban wastewater were included as eligible actions in the long-term investment strategy of Ministry of Agriculture, Food Sovereignty and Forests (MASAF) (Ferrigno & Zucaro, 2023), receiving approximately the 3% of the available budget for the period 2018-2023 (source: DANIA – National Database of investments for Irrigation and Environment). The Italian CAP Strategic Plan for the 2023-2027 programming period, gives the possibility for funding these interventions, where compliant with WRR (D'Alicandro, 2024).

The proposed methodology is flexible and applicable from various analytical perspectives. It can be replicated in other regions and at different territorial scales, as it relies on data that are uniformly structured and collected across the national and European levels – thanks to databases developed in line with EU policies such as the WRR (EU) 2020/741.

The methodology will be further developed to support the creation of a comprehensive national database that incorporates additional factors influencing the reuse of treated wastewater for irrigation, such as predominant irrigation methods, the presence of environmental constraints (e.g., nitrate-vulnerable zones), and the availability of storage facilities. Furthermore, the quantitative dimension, concerning the balance between the amount of treated wastewater potentially provided by WWTPs and the irrigation requirements in the surrounding areas, is a relevant and parallel line of research, which lies beyond the primary scope of this study. A cost-benefit assessment based on the value of the affected crops could be an additional future direction for expanding and integrating the methodology applied here.

Conflicts of interest

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