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Challenges and opportunities for more efficient water use and circular wastewater management. The case of Campania Region, Italy

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ABSTRACT

By 2050, global demand for water is expected to increase by some 55% due to population growth and urbanization. The utilization of large amounts of freshwater in the world, generate huge volumes of wastewater of which, globally, more than 80% is discharged without treatment, thus causing impacts on aquatic ecosystems, human health and economic productivity. More sustainable practices of wastewater management are expected as a way towards circular bioeconomy (CBE) processes, whose goal is to implement closed systems promoting the systematic use of recycling, reuse and recovery of bioproducts and by-products and the reduction of waste generation. This approach, if adopted in the water and wastewater sector, can ensure environmental, economic and social benefits. The reuse of wastewater, on the one hand, reduces the volume of wastewater and the pressure on water bodies; on the other hand, the recovery of nutrients (P or N) and/or other high value bioproducts (biogas, cellulose, biopolymers) from wastewater offers numerous advantages in terms of supplying new raw bio-based materials that can be refed back to supply chains (thus substituting fossil resources) and, at the same time, producing cleaner water to be reused. Nevertheless, while in Europe many industries have demonstrated the ability to recycle and reuse water, in many regions of Italy the sustainable management of water and wastewater is not yet consolidated. In this study we explore the available technological, economic and environmental options concerning water use and wastewater treatment and we apply them to design appropriate scenarios for improved use efficiency and circular management. A comprehensive literature review of the most promising wastewater treatment processes for resources and energy valorization was conducted. The recovery of PHAs, struvite, nitrogen and algal biomass, as potential substitutes for conventional PET, phosphate and nitrogen chemical fertilizers and electricity, respectively, in addition to reusable treated water, were hypothesized and carefully discussed. Resulting scenarios are tested against the present situation of Campania Region (situated in Southern Italy) based on population and demand statistics, in order to develop strategies and policies potentially applicable locally and elsewhere.

1. Introduction

Water is inextricably linked to the development of a country: it is central to the production and preservation of a host of benefits and services for people and ecosystems. But unsustainable development, together with continuous population growth and accelerated urbanization, is placing pressure on water resources: by 2050, global demand for water is expected to increase by some 55%, due to growing demand from manufacturing (+400%), thermal electricity generation (+140%) and domestic use (+130%) (Boretti and Rosa, 2019; United Nations, 2020). For these reasons, the World Economic Forum ranked the water crisis and its risks as one of the main environmental risks worldwide (World Economic Forum, 2014). Recognizing the growing challenge of water scarcity, wastewater management has also found recognition in one of the 17 Sustainable Development Goals, namely the SDG 6, which aims to, among others, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater by 2030 (Masi et al., 2018; UN General assembly, 2015). Moreover, the availability of safe and sufficient water supplies cannot disregard how wastewater is managed. Almost half of the global freshwater is mainly consumed by agriculture (through evapotranspiration in irrigated cropland). The remaining half is released into the environment as wastewater in the form of municipal and industrial effluent and

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Abbreviation index

AnMBR	Anaerobic Digestion/Membrane filtration
ARERA	Regulatory Authority for Energy, Networks and Environments
ARPAC	Regional Agency for Environmental Protection in Campania Region
ARPAE	Regional Agency for Environmental Protection in Emilia Romagna Region
BESs	Bioelectrochemical systems
CAS	Conventional Activated Sludge
CE	Circular Economy
CBE	Circular Bio-Economy
CJEU	Court of Justice of the European Union
COD	Chemical Oxygen Demand
DFOB	Desferrioxamine B
DFOE	Desferrioxamine E
ERDF	European Regional Development Fund
EU	European Commission
FBR	Fluidized Bed Reactor
GVA	Gross Value Added
HRAP	High Rate Algal Ponds
ISTAT	National Institute of Statistic
IWW	Industrial Wastewater
LCA	Life Cycle Assessment
MAP	Magnesium Ammonium Phosphate
MBR	Membrane Bioreactors
MBBR	Moving Bed Biofilm Reactor
MMC	Mixed microbial culture
MWW	Municipal Wastewater
OMBRs	Osmotic Membrane Bioreactors
OMV	Olive mill wastewater
PBPs	Phycobiiproteins
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoates
SBR	Sequencing Batch ReactorSCP: Single Cell Protein
UASB:	Up-flow Anaerobic Sludge Blanket
WWTPs	Wastewater Treatment Plants
SDG	Sustainable Development Goals

agricultural drainage water, thus causing impacts on aquatic ecosystems, human health and economic productivity (Smol et al., 2020; Voulvoulis, 2018).

According to UN World Water Development Report (2017), more than 80% of global wastewater is discharged without treatment, therefore, wastewater still represents an 'untapped resource' (United Nations, 2017). In this sense, more sustainable practices of wastewater are expected as a way towards the Circular Economy (CE) in the water and wastewater sectors. In fact, in the second communication of 2015 "Closing the loop - An EU action plan for the Circular Economy" (European Commission, 2015), the reuse of treated wastewater in safe and cost-effective conditions has been identified a valuable but under-used way of increasing water supply and alleviating pressure on over-exploited water resources in the EU (Smol et al., 2020).

In addition to the use in agriculture for irrigation of crops (food and non-food), pastures and aquaculture, wastewater can be re-used for irrigation for landscape purposes (parks, school courtyards, cemeteries), in the industrial sector (as cooling or process water), for recreational and environmental uses (as lake recharging or ponds and waterways), as well as for potable (refill of the underground aquifer) and non-potable uses (such as for fire protection systems, air conditioning, vehicle washing, toilets, etc.) (De Gisi et al., 2017).

1.1. *Wastewater as a resource*

Nevertheless, from a CE perspective, WWTPs offer a double value proposition (De Gisi et al., 2019): they are not only useful to remove pollution (end-of-pipe approach), but they are real factories (or biorefineries) capable of producing water to reuse as well as of recovering value added resources from wastewater and sewage sludge (resource-oriented approach) (Eusebi et al., 2020; Papa et al., 2017; Puyol et al., 2017). This perfectly mirrors the key concept of the circular bioeconomy strategy which can be defined as the "*production of renewable biological resources and the conversion of these resources and waste streams into value-added products, such as food, feed, bio-based products and bioenergy*" (European Commission, 2018). Indeed, as well as providing a safe alternative source for freshwater, wastewater can also be seen as a potential source of raw materials (De Gisi et al., 2017). These value-added products are recoverable resources with an enhanced value stemming from some extra process or product that can also contribute to offset the adverse environmental impacts of wastewater treatment caused by the high energy consumption (Hao et al., 2019). Examples of recoverable resources are: inorganic nutrients (nitrogen and phosphorus) and/or organic, biopolymers, heat, heavy metals, cellulose, mineral nutrients, etc. (Akyol et al., 2020; Caspersen and Ganrot, 2018; Crutchik et al., 2018; Smol et al., 2020).

Several technologies to recover nutrients, that can be used as soil improvers or fertilizers, are being investigated worldwide: from more traditional methods, such as chemical precipitation and adsorption, to more advanced approaches, such as bioelectrochemical systems (BESs) and osmotic membrane bioreactors (OMBRs) (Egle et al., 2015; Eusebi et al., 2020; Ye et al., 2020).

Organic polymers like cellulose and PHAs can instead be recovered by sieving (Ruiken et al., 2013) and by bacterial fermentation, respectively. These polymers can then be reused for energy purposes (including fermentation to produce biogas or incineration to produce bioenergy) or, alternatively, to replace raw materials in construction (asphalt, concrete, insulation) and/or in the production of cardboard and paper (Zijp et al., 2017) and bioplastics (Mannina et al., 2020; Valentino et al., 2017). Moreover, integrated systems such as membrane bioreactors, namely MBRs - integration of membrane filtration with conventional activated sludge (CAS) treatments - and AnMBR - integration of anaerobic digestion treatment with membrane filtration -, are being explored to simultaneously recover clean water, energy, and nutrients from wastewater (Akyol et al., 2020; Song et al., 2018).

In Europe, many industries have made promising progresses in water management and some have demonstrated the ability to recycle and reuse water to achieve zero net consumption (Voulvoulis, 2018). However, in many countries, as in Italy, the sustainable management of water resources is not yet consolidated. ARERA, the Regulatory Authority for Energy, Networks and Environments, in its 2019 annual report, estimates a reuse of just 4% of the volume of treated wastewater, mainly for irrigation, against an already available potential of 20% of reusable wastewater (ARERA, 2019). Regarding the recovery of resources from wastewater, Papa et al. (2017) conducted a survey on the implementation of these activities in WWTPs, showing that more than 60% of the Italian plants does not carry out any type of recovery. The survey revealed that the most common types of recovery are the material from excess sludges and treated effluents for internal reuse (for washing equipment or other types of plant maintenance). Whilst the recovery of energy, through biogas production, occurs only in large plants, no cases of polymers recovery were detected in the Italian WWTPs (Papa et al., 2017). The poor implementation of these recovery actions may depend on technical, economic, social and legislative factors. For example, since there is a poor legislation on quality standards for the recovered products, there are several market uncertainties that may discourage economic investments (United Nations, 2017). Some progresses have been made in the development of a circular bioeconomy national strategy and an action plan on sustainable consumption and production in the light of the 2017 sustainable development strategy (Ministero dell'Ambiente e della tutela del territorio e del mare, 2017). However, actual implementation in Italy is still slow and, in particular, the center and south of the country perform less well in waste management than the north. A sadly known case, the investigated area of the present paper, is the Campania Region (situated in Southern Italy) that is continuing to pay fines for poor waste management, after it was sanctioned by the Court of Justice of the European Union (CJEU) for its previous waste management policies (European Commission, 2019).

The Regional Agency for Environmental Protection in Campania Region, responsible of the waste management monitoring, reports that in 2006 no cases of reuse of treated wastewater were known in Campania Region neither in the agricultural nor in the industrial sectors and the exact quantities of sewage sludge were not known (ARPAC, 2006). After approximately 40 years and 700 million € invested (as for 2015), wastewater is still of great concern in Campania Region (Lofrano et al., 2015) where over 800 million € has been recently allocated by the European Regional Development Fund (ERDF) for water management 2014–20 (European Commission, 2019). Together with economic investments, a step ahead toward a more circular wastewater management requires the identification of management routes capable of maximizing recycle and recovery benefits (Buonocore et al., 2018).

1.2. *The objectives of this research*

1.2.1. *This study has three main aims*

- i To perform a careful quantitative assessment of the Campania Region's water flows (taken as an example of water demand in a given area) and,
- ii To design potential circular scenarios of wastewater treatment, capable to decrease water demand and recover valuable resources.
- iii To quantify potential valuable by–products from circular wastewater treatment, to meet water, energy, nutrients and biomaterials demand at local scale.

For better accomplishment of these goals we conducted a comprehensive literature assessment of the wastewater treatment processes, for resources and energy valorization, while taking into account the circular bioeconomy concept, in order to identify suitable scenarios and potential benefits for Campania Region, considered a useful test for other areas.

The article is organized as follows. Section 2 describes the methodology adopted both for the data gathering and for the research, selection, and analysis of publications, as well as the inclusion and exclusion criteria. Section 3 and Section 4 contain the results and a discussion. Section 3 firstly presents the results of a literature review regarding the most promising circular pathways and then designs a set of viable scenarios allowing wastewater treatment towards final products. These scenarios are then tested against the current water demand and wastewater management system in Campania Region, discussing the potential environmental and economic advantages potentially gained by the implementation of these pathways in Campania Region. Such application to the Campania case study is an important test for application of the same procedure in developing countries and elsewhere areas with wastewater burdens.

2. Materials and methods

2.1. *Water uses in the study area*

In the present work, water flows in the most water-demanding economic sectors and the potential amount of urban wastewater treated were estimated in Campania Region (Southern Italy), a Region with a population of about 5.8 million people (ISTAT - Istituto Nazionale di Statistica, 2020a) divided into 5 provinces (Avellino, Benevento, Caserta, Salerno, Metropolitan City of Naples) and encompassing 550 municipalities. Campania Region falls (together with Abruzzo, Basilicata, Calabria, Apulia, Lazio and Molise) within the Hydrographic District of the Southern Apennines (Fig. 1) (Repubblica Italiana, 2006), which in 2018 was ranked second (after Hydrographic District of the river Po) for the highest freshwater withdrawal for household use (ISTAT - Istituto Nazionale di Statistica, 2020b). Compared to the other regions of the same hydrographic district, Campania Region is a particularly interesting case for: the availability of water resources, the amount of water withdrawn for drinking use and the water exchanges with nearby regions, which translates into about 1983.7 m^3/person in the year 2018.

First of all, according to the Water Management Plan of the District and the Regional Water Protection Plan, Campania Region has a larger water availability than other Regions of the District. In fact, as can be seen in Fig. 2, the availability of surface water (8801 Mm^3/year) corresponds to 40% of the total of the District, while the availability of groundwater resource (2778 Mm^3/year) accounting for the 44% of the total of the District (Fig. 2) (Distretto Idrografico dell'Appennino Meridionale, 2016; Regione Campania, 2020).

Nevertheless, in the Hydrographic District of the Southern Apennines there is an articulated and strongly interconnected water system characterized by significant interregional surface water and groundwater transfers (several underground water bodies are interconnected between the various regions) (Distretto Idrografico dell'Appennino Meridionale, 2016). Therefore, in Campania Region as well as in other regions of the District, the availability of water sources also relies on the water exchanges involving neighboring regions (Table 1). Campania imports 202 million cubic meters (Mm^3) of water per year, partly from the Gari River of the Lazio Region and partly from the sources of Sammucro, San Bartolomeo and Biferno and from Campo Pozzi Peccia of the Molise Region. At the same time, it exports 248 Mm^3 of water per year: from the sources of Cassano Irpino and Caposele and the Conza dam to Apulia and Basilicata Regions. The total water availability is therefore equal to 11, 534.12 Mm^3/year (Regione Campania, 2020).

In addition to the high availability of water resources, it is important to take into account that in 2018, according to ISTAT data (ISTAT - Istituto Nazionale di Statistica, 2018a), Campania Region ranked second (after Lazio Region) for the highest freshwater withdraw for household use, compared to the other Regions of the District (Table 2). Table 2 shows freshwater withdrawal per capita calculated by dividing the total freshwater withdrawal by the number of inhabitants for each region. In Campania Region, even if the volume of freshwater withdrawn per capita is lower than in the other regions, the total volume withdrawn is high due to the large number of residents in 2018.

2.2. *Data sources used to estimate regional water flows*

In the first part of this work, freshwater flows and the amount of urban wastewater treated were estimated using statistical data and/or reports from Institutional/Statistical Organization and information obtained through contacts with the Campania Region and ARPAC (Regional Agency for Environmental Protection of the Campania Region). At national level, statistics available on freshwater flows in the various economic sectors are usually based on estimates provided by different organizations and institutions, thus entailing great heterogeneity and poor standardization or comparability of data (Vignani et al., 2016). Data are also limited at the regional level where data are often

Fig. 1. Location of campania region.

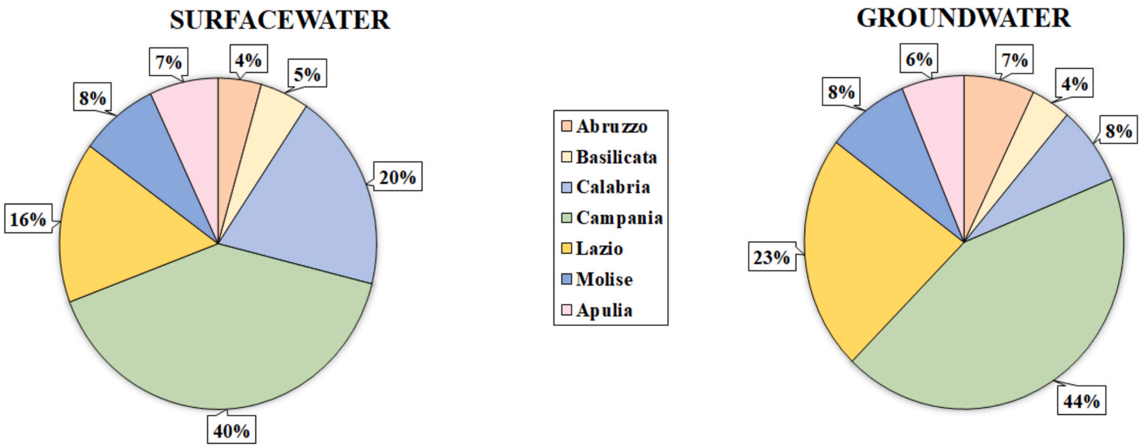

Fig. 2. Availability of surface water and groundwater in the Hydrographic District of the Southern Apennines (Distretto Idrografico dell'Appennino Meridionale, 2016).

Table 1
Interregional transfers involving Campania. Data source: Regione Campania (2020).

Region	Volumes imported (Mm^3/year)	Volumes exported (Mm^3/year)
Lazio	95	–
Molise	106.7	–
Apulia	–	231.8
Basilicata	–	16
Total volume	**201.7**	**247.8**

estimated or outdated. In this regard, after a careful screening of the different sources, estimates were made to get a general picture of the different water flows in Campania Region (Distretto Idrografico dell'Appennino Meridionale, 2016; Regione Campania, 2020).

The analysis focuses on the estimation of the main water flows in the household, industrial and primary sectors for the reference year 2018. The methodological approach is briefly described below. Withdrawals, consumption and losses in the household sector were estimated taking into consideration data of the latest available water census of 2015 (ISTAT - Istituto Nazionale di Statistica, 2017a) and were adjusted to the population residing in the Region in the 2018. Data on water used by the industrial sector was not available at the regional level neither in the

Table 2
Withdrawals of freshwater for household use by region of the Hydrographic District of the Southern Apennines for the reference year 2018. Data source: ISTAT - Istituto Nazionale di Statistica (2018a).

Region	Volume withdrawn (Mm^3)	Population 2018	Withdrawal (m^3/per capita)
Abruzzo	295.5	1,313,388	224.8
Basilicata	288	564,993	510
Calabria	405.6	1,951,909	207.6
Campania	932.7	5,814,276	160.6
Lazio	1157	5,887,887	196.3
Molise	226.7	307,055	738.3
Apulia	171.5	4,038,647.5	42.3

national statistics nor in institutional reports. In fact, withdrawal and/or consumption of water in the industrial sector is more difficult to estimate due to the heterogeneity of the sector itself. Water uses in manufacturing industries are manifold: it can be used for cleaning, heating, cooling, steam generation, as a solvent or as a constituent part of the product itself (for example in the beverage industry) (ISTAT - Istituto Nazionale di Statistica, 2019). Indeed, processes and products require different amounts of water. In Italy there is a lack of uniform estimates on the quantification of industrial water flows and the few statistics available on Italian industrial activities show a great fragmentation of information, heterogeneity of data and lack of standardization (Vignani et al., 2016). Moreover, unlike the household sector, there is no widespread monitoring system. The first estimate at national level of the volume of water used by the manufacturing industry with sector breakdown is that provided by ISTAT in 2012, the results of which are presented by Vignani et al. (2016). Currently, ISTAT reports only the estimate on the volume of water used, as a production input, by the manufacturing industry in 2015, based on physical units of product, divided by type within each manufacturing sector (ISTAT, 2019). Concerning Campania Region, actual data on the consumption of water for industrial use are not available and the only approximate estimate was performed by upscaling the consumption of water per employee in the industrial activities of Province of Salerno (of which water consumption was quantified) to all employees of Campania Region (Regione Campania, 2020). In order to estimate water use in regional industries, the intensity of water use per sector at national scale (i.e. Italy) was used. Water use intensity in a particular economic sector is defined, in a similar way as the indicators on material and energy intensity, as the volume of water used per unit of gross value added (GVA) and measures the pressure of the economy on water resources in relation to its economic impact, a relevant indicator for sustainable development and resource efficiency policies (EUROSTAT, 2015). Water use and GVA data, broken-down by economic activity (26[1]) (EUROSTAT, 2008), were taken from the work by Vignani et al. (2016) and ISTAT (ISTAT - Istituto Nazionale di Statistica, 2012), respectively. Water intensity indicator for Italy in the year 2012 was calculated dividing the volumes of water directly withdrawn by an economic activity for own use by value added. Being the data on GVA of the economic activities in Campania Region available (ISTAT - Istituto Nazionale di Statistica, 2017b), the calculated water intensity was scaled up to obtain estimation of water withdrawal for each industrial sub-sector (by multiplying the water intensity of a specific industrial sub-sector by the GVA of that sector in Campania Region). Detailed calculations and data are provided in the Appendix. Of course, since this estimation is based on an indicator computed at national level, it may hide spatial and technological variability in water use for specific supply chains. As regards the primary sector, estimations on the water consumption in the agricultural sector were carried on taking into account the data available in the Water Management Plan (Distretto Idrografico dell'Appennino Meridionale, 2016). For the livestock sector, water consumption was estimated on the basis of the number heads of livestock and the adequate water supply per animal per year. While data regarding the number heads of livestock were collected from ISTAT (ISTAT - Istituto Nazionale di Statistica, 2018b), water supplies for each type of animal (bovine, buffaloes, ovine, caprine, pigs) were taken from literature (ARPAE - Agenzia Regionale per la Protezione Ambientale in Emilia Romagna, 2015) (Table 3). Furthermore, the water losses of the industrial and primary sectors were not evaluated.

Finally, urban wastewater was estimated by taking into account wastewater produced by the drinking water (Municipal Wastewater - MWW) and wastewater produced by industrial sectors (Industrial Wastewater – IWW) sectors and basing on the consultation with local experts in the field.

Firstly, using the last census of wastewater treatment plants (ARPAC - Agenzia Regionale per la Protezione Ambientale in Campania, 2020), the largest plants located in Campania Region were selected depending on their maximum capacity, expressed as population equivalent (Table 4) (Braga and Polverini, 2018). Later, the volume of wastewater potentially treated by wastewater plants was obtained by taking as reference a similar Italian wastewater plant located in the city of Bologna (Migliori et al., 2008). Finally, data from the ISTAT water census on the production of urban wastewater expressed in millions of population equivalent were used (ISTAT - Istituto Nazionale di statistica, 2017) to estimate the amount of wastewater treated in Campania Region, expressed in Mm^3. However, it is important to underline that the volume obtained is an estimation of the volume as it considers the maximum potential of the chosen plants and is affected by uncertainty as it is based on estimates obtained from the available data which, even in this case, were insufficient and fragmented.

2.3. Literature review of options for wastewater treatment

In the second part of this work, examples of wastewater recovery according to the principles of circular bio-economy were searched through a careful review of the literature. For the search of viable circular scenarios, scientific works available in Scopus database were considered. In order to obtain an accurate review of the existing literature and a full-bodied data set, the following keywords, "circular AND economy AND wastewater" were introduced into the database using the

Table 3
Data used to estimate water consumption in the livestock sector in 2018.

Livestock	Number heads (2018)	Total water consumption per year (m^3/year)
Bovine	195,004	8,190,168
Buffaloes	298,047	12,517,974
Ovine	204,395	204,395
Caprine	39,999	39,999
Pigs	104,978	839,824
	TOTAL	21,792,360

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[1] **Section B**: Mining and quarrying minerals; **Section C**: 10 - Manufacture of food products; 11 – Manufacture of beverages; 12 – Manufacture tobacco products; 13 – Manufacture of textiles; 14 – Manufacture of wearing apparel; 15 – Manufacture of leather and related products; 16 – Manufacture of wood and products of wood and cork, except furniture, manufacture of articles of straw and plaiting materials; 17 – Manufacture of paper and paper products; 18 – Printing and reproduction of recorded media; 19 – Manufacture of coke and refined pretroleum products; 20 – Manufacture of cheicals and chemical products; 21 – Manufacture of basic pharmaceutical products and pharmaceutical preparations; 22 – Manufacture of rubber and plastic products; 23 – Manufacture of other non-metallic mineral products; 24 – Manufacture of basic metals; 25 – Manufacture of fabricated metal products, except mahinery and equipment; 26 – Manufacture of computer, electronic and optical products; 27 – Manufacture of electrical equipment; 28 – Manufacture of machinery and equipment n.e.c.; 29 – Manufacture of motor vehicles, trailers and semi-trailers; 30 – Manufacture of other transport equipment; 31 – Manufacture of furniture; 32 – Othe manufacturing; 33 – Repair and installation of machinery and equipment.

Table 4
Largest wastewater treatment plants in Campania Region, serving from 500,000 to 2,000,000 population equivalent. Data source: ARPAC - Agenzia Regionale per la Protezione Ambientale in Campania (2020).

Province	Municipality	Wastewater type	Maximum capacity (population equivalent)	Wastewater treated (Mm^3)
CE	Marcianise	Municipal (60%)/Industrial (40%)	803,000	42
CE	Orta di Atella	Municipal	886,000	46
CE	Villa Literno	Municipal (85%)/Industrial (15%)	632,900	33
NA	Castellammare di Stabia	Municipal	500,000	26
NA	Napoli	Municipal	1,750,000	91
NA	Pozzuoli	Municipal	1,800,000	94
SA	Capaccio	Municipal	175,000	9
SA	Salerno	Municipal	700,000	36
SA	Scafati	Municipal	648,000	34
Total amount			7,894,900	**411**

Boolean operator "AND", whose search yielded 209 documents. A time interval was then set from the year 2015–2020 from which 194 documents were obtained. This interval was chosen because in 2015 the European Commission adopted an action plan to accelerate European transition to a circular economy, stimulate global competitiveness and promote sustainable economic growth (European Commission, 2015). Later on, a refinement of the search was accomplished by restricting the search to articles and reviews, thus obtaining 165 documents. Moreover, only papers from countries belonging to European Union were selected, in accordance with the aforementioned directive; this criteria produced 118 documents, out of which those not in English were excluded, achieving a the final body of 117 articles (96 articles and 21 reviews) for which a more detailed content analysis was carried out. The research methodology is shown in Fig. 3.

The references cited in the selected publications were used as secondary sources; however, this resulted in only a few articles, which may indicate the wide-ranging of the initial research. The content analysis aimed at gathering quantitative information on the recovery of resources from wastewater in order to hypothesize possible scenarios for Campania Region and quantify possible environmental benefits. Despite the deluge number of articles found in scientific literature, out of the 117 selected papers and reviews and cited references, only very few allowed a numerical estimate of achievable circular benefits and therefore scenarios, which is the main goal of the present study. Criteria for selection of scenarios from literature is based on clear and comprehensive description of suggested circular processes as well as quantification of achievable benefits in all process steps, from wastewater to final treated water and by–products. The goal is to provide viable options for wastewater treatment and profitable generation of treated water and selected by–products, achievable with presently affordable technology. Potential options without numerical details have been helpful for deeper understanding but have not been fully integrated into the design of scenarios (see Sections 3.1, 3.2 and Fig. 4).

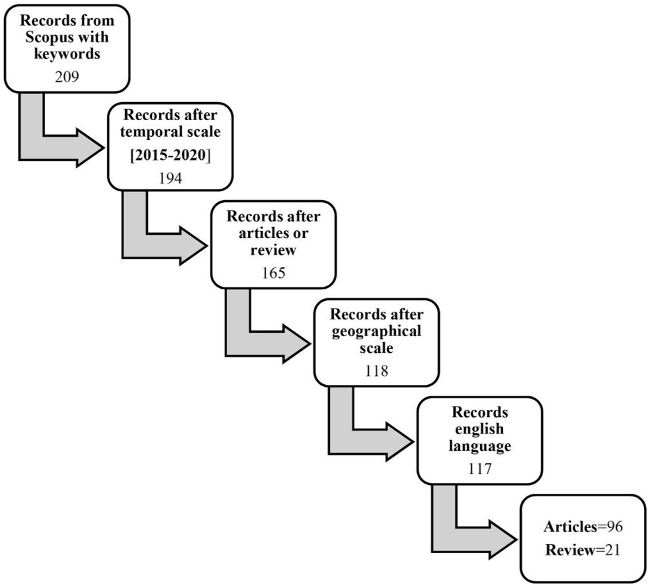

Fig. 3. Framework developed for the screening of scientific works.

3. Results and discussion

The goal to design suitable scenarios for wastewater treatment and extraction of treated water and by–products through a viable chain of processes required a deep literature search, in order to identify circular pathways. Although the search issued several interesting articles and review papers have been carefully analyzed, only few studies specifically quantified the value-added products obtainable from wastewater and, therefore, they have been used to design circular scenarios in Campania Region (and potentially other similar areas). These scenarios are discussed by highlighting their pros and cons using the full body of articles found in literature.

3.1. Pilot circular studies from literature

In order to help design suitable scenarios, the review – mainly based on about 100 papers resulting from selection – allowed to identify additional steps and products that could be recovered from wastewater. Unfortunately, most often no full numerical estimates were available as most of the reviewed papers only dealt with pilot studies, namely preliminary small-scale cases aimed at better understanding performance design, prior to full-scale research projects. However, pilot studies – described in the following – have been very useful for us to fully understand the viability of a set of scenarios, leading to Section 3.2 and Fig. 4.

A wide range of products such as nutrients, energy, biomolecules, metals, organic and inorganic compounds can be recovered from different typologies of wastewater, some of which are described in the following as pilot studies, to show the variety and richness of wastewater treatment processes, and summarized in Table 5a.

(i) Interesting cases involving bioenergy production can be described as follows:
  - The treatment of dairy wastewater with microalgae for the removal of nutrients was investigated by Hemalatha et al. (2019). The sugars produced by microalgae via photosynthesis (especially glucose) were used for the production of bioethanol through yeast fermentation, using *Saccharomyces cerevisiae* in so contributing to bioenergy production.
  - Gallium (Ga3+) recovery from wastewater of the low gallium wafer manufacturing industry can contribute to the development of renewable energy generation and energy efficient systems, according to Jain et al. (2019). It can be used in solar photovoltaic cells and light emitting diodes. Due to its

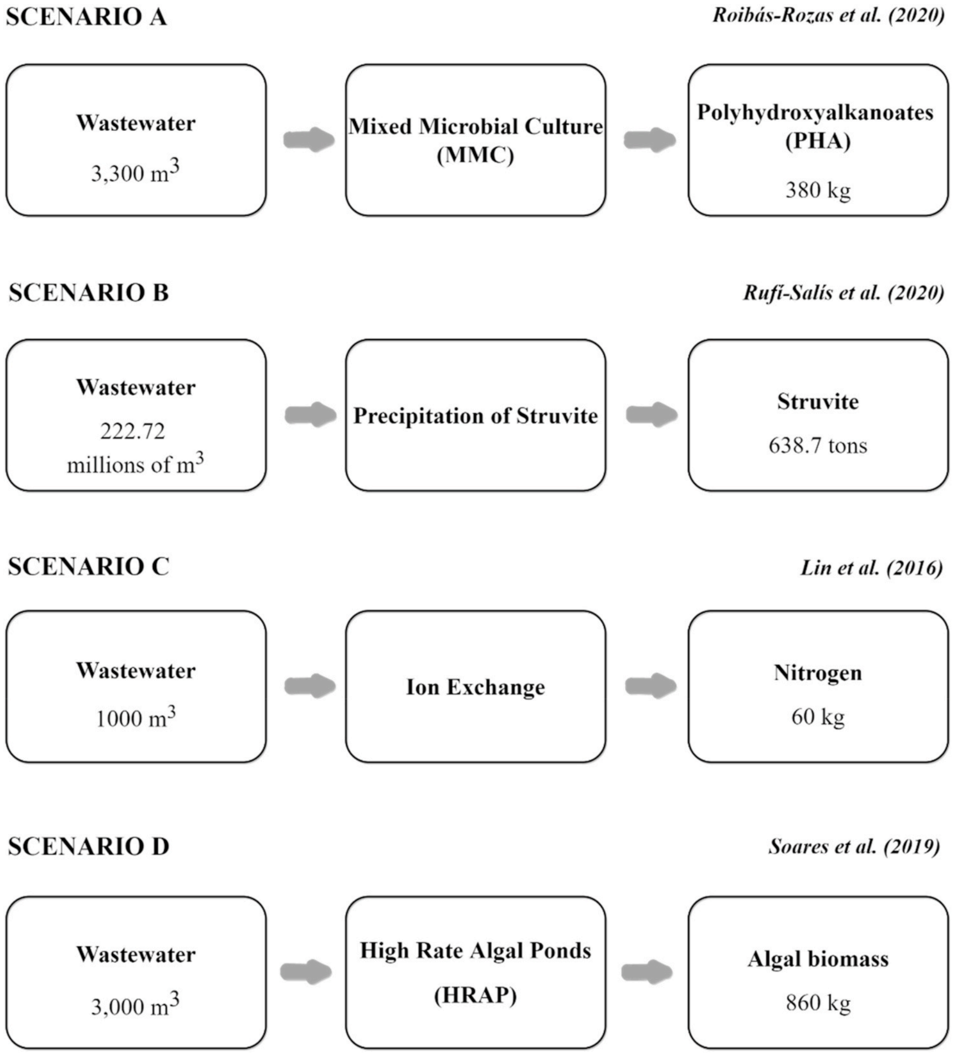

Fig. 4. Possible circular scenarios from wastewater treatment (Lin et al., 2016; Roibás-Rozas et al., 2020; Rufí-Salís et al., 2020; Soares et al., 2019).

usefulness, its demand is strongly growing and as a result it has been identified by the EU as a critical and risky commodity. Therefore, the development of technologies that allow the recovery of this metal, in addition to improving conventional mining activities, can help ensuring its future availability. The recovery process consists in the use of desferrioxamine B (DFOB) and desferrioxamine E (DFOE) siderophores which form complexes with gallium that are then recovered by application of a reversed-phase chromatography column.

(ii) Proteins and other biochemicals characterized by important nutraceutical and pharmaceutical properties can be obtained via agro–industrial wastewater valorization:

- The recovery of total phenols, hydroxytyrosol and tyrosol from oil mill wastewater (OMW) by liquid-liquid extraction with solvent was evaluated by Kalogerakis et al. (2013). Various organic solvents have been used for the process, such as diethyl ether, ethyl acetate and a mixture of isopropyl alcohol and chloroform. The results showed that treating 1 m^3 of oil mill wastewater with ethyl acetate could result in 0.25 kg of hydroxytyrosol, 0.062 kg of tyrosol and 3.44 kg of total phenols. Furthermore, in this study, a life cycle assessment was conducted to evaluate the most environmentally-sound extraction technique and it was shown that the best solution was the extraction with ethyl acetate which causes low environmental impacts and high recovery yield of antioxidant. The recovery of phenols from oil mill wastewater is advantageous, as these compounds have antioxidant properties by acting by eliminating free radicals in the cells and thus providing protection against oxidative stress in biomolecules such as proteins, lipids and DNA. Moreover, due to their properties, they can act as raw materials in the cosmetic, pharmaceutical and food industries for the production of new products.
- Chen et al. (2020) conducted a study on an agro-industrial wastewater valorization technology using wastewater of a fruit juice processing facility to produce SCP (single cell protein). An unconventional processing system, called AgroCYCLE, was adopted to extract these proteins, that has been tested at pilot scale and based on a nutrient recovery/valorization technology to produce SCP proteins. These proteins can be used as substitutes for protein-rich foods in both human and animal diets such as: meat substitutes, sports drinks and bars, alternative drinks to milk, especially for children, food supplements or as feed for livestock/fish and pets.
- The production of phycobiliproteins (PBPs) through the cultivation of microalgae such as Nostoc sp., Arthrospira platensis and Porphyridium purpureum, in industrial wastewater is also an interesting option (Arashiro et al., 2020). Phycobiliproteins are auxiliary pigments, water-soluble and highly fluorescent proteins which, in addition to playing an important role in the metabolism of microalgae pigmentation, have various properties such as

Table 5

Literature main cases of wastewater treatment, a. Pilot studies of resource recovery from wastewater, b. Circularity review papers regarding the resources' recovery from wastewater.

Product recovery	Pathway	Reference
Ethanol	Wastewater treated with microalgae and fermentation of microalgae's sugars	Hemalatha et al. (2019)
Ferrous oxalate	Reduction reaction	Kim and Baek (2019)
Gold	Filamentous endophyte fungus	Xu et al. (2019)
Clacium fluoride	Crystallization process, by means of a fluid bed reactor	Zeng et al. (2019)
Single cell protein (SCP)	AgroCYCLE system	Chen et al. (2020)
Phycobiliproteins (PBPs)	Cultivation of microalgae	Arashiro et al. (2020)
Gallium (Ga)	Formation of siderophores complexes and recovery by a reversed-phase chromatography column	Jain et al. (2019)
Phenols	Liquid-liquid extraction with solvent	Kalogerakis et al. (2013)

Main topic	Title	Reference
Nitrogen recovery from wastewater	From removal to recovery: An evaluation of nitrogen recovery techniques from wastewater	Beckinghausen et al. (2020)
State of the art of wastewater nutrient recovery technologies	New frontiers from removal to recycling of nitrogen and phosphorus from wastewater in the Circular Economy	Robles et al. (2020)
Moving bed biofilm reactor (MBR) systems	Moving bed biofilm reactor as an alternative wastewater treatment process for nutrient removal and recovery in the circular economy model	Leyva-Díaz et al. (2020)
Efficiency of biodiesel production from urban wastewater lipids	Assessment of the production of biodiesel from urban wastewater-derived lipids	Frkova et al. (2020)

antioxidants, anticancer, anti-inflammatory, antiangiogenic and neuro and hepatoprotective properties. Furthermore, they can be used as natural dyes in the nutraceutical, cosmetic and pharmaceutical industries and in textile industries. The production process of these proteins is articulated in several steps: the growth of algae biomass, the subsequent removal of nutrients and the production of phycobiliproteins. The pigments mostly extracted from microalgae biomass are: phycocyanin, allophycocyanin and phycoerythrin.

(iii) Recovery of metals and other chemicals from industrial wastewater has also shown to be an interesting pathway, to decrease pollution and at the same time to provide high value products:
- Removal of ferrous oxalate and other metals from soil washing wastewater throughly a two-step reduction reaction was investigated by Kim and Baek (2019): under mildly reduced conditions, the ferric iron in the wastewater is reduced to ferrous iron, which forms a compound with oxalate and precipitates as an oxalated ferrous phase.
- The possibility of recovering gold from electronic wastewater through adsorption technology was studied and proved by Xu et al. (2019). In this case, Phomopsis sp. XP-8 is used, a filamentous endophytic fungus that has a great potential of selectively recovering gold from electronic wastewater since, due to its mycelial lifestyle, it has an extremely high surface/volume ratio, leading to an adsorption capacity relatively higher than bacteria.
- Zeng et al. (2019) investigated the possibility of removing fluorine and recovering calcium fluoride from rare earth fusion wastewater using a crystallization process, via a fluidized bed reactor (FBR) with silica sand. In this work, FBR was applied to a typical fluorine-containing rare earth wastewater foundry.

In order to give a comprehensive overview of the circular wastewater treatments, a careful screening of scientific literature review papers was also performed. Out of the 21 review papers, four were selected, whose findings are shown in Table 5b. In particular, Beckinghausen et al. (2020), carried out a survey on different technologies for recovering nitrogen from wastewater in order to evaluate their efficiency and feasibility. They concluded that further energy and economic analyses are needed in order to make these technologies suitable for large-scale implementation. Robles et al. (2020) described the state of the art of nutrient recovery by examining the benefits and limitations of different recovery technologies; they conclude too that more research is needed to optimize these recovery technologies and broaden their applicability. Frkova et al. (2020) evaluated the technical feasibility of removing lipids from urban wastewater for biodiesel production and demonstrated that a non-negligible amount is extractable for the production of biofuels. However, the study also found that lipid recovery methods are still limited and none of them are currently used on a large scale. Leyva-Díaz et al. (2020) proposed a moving bed biofilm reactor (MBBR) as a new technology for water reuse, removal and recovery of nutrients from wastewater. They proved that the MBBR system is also suitable for the production of high-quality reclaimed wastewater.

3.2. Design of viable circular wastewater scenarios

Considering the large number of recovery options and pilot studies from literature, a selection was unavoidable. As clarified in Methods, selection criteria to identify processes applicable from wastewater to final products were applied, so that the following scenarios could be identified as viable and suitable (Fig. 4).

The first selected scenario, namely Scenario A, is built on a study by Roibás-Roazas et al. (2020) which compares a linear approach and a circular approach for wastewater treatment. This approach concerns the production of PHAs from wastewater from a fish canning industry, using a mixed microbial culture (MMC). They evaluated the environmental benefits of PHA production from wastewater, through life cycle assessment (LCA). The results of the LCA assessment of the linear and circular systems showed that the implementation of the circular approach determine approximately a 25% performance's improvement for nine of the analyzed environmental categories. These compounds may be therefore be very promising as, being biodegradable polymers and with a high propensity for recycling (Dwivedi et al., 2020), they could replace conventional petrochemical plastics, well-known sources of environmental pollution (Sharma et al., 2020). The study was selected as a potential scenario for Campania Region as it provides useful data regarding the quantity of PHA that can be produced from wastewater. The PHA production process from MMCs usually includes three stages (Kourmentza et al., 2017) encompassing: (a) complex substrates such as wastewater from food manufacture are fermented to obtain volatile fatty acids as precursors for PHA production; (b) a population of microorganisms with high PHA production capacity is selected and enriched; finally, (c) the microbial biomass is supplied with volatile fatty acids from the first stage to maximize PHA accumulation. When the cells reach their maximum PHA content, they are harvested and directed to extraction processes. This technique of PHA extraction by MMC is advantageous from an economic point of view: it is inexpensive and allows to use a wide range of organic substrates, including waste/excess flows, without prior sterilization of the substrate and can easily produce a wide range of PHA co-polymers with different compositions utilizing different feedstocks. The cost reduction derives mainly from operations performed in non-sterile conditions, and from their consequent energy savings, and from MMC's greater adaptability to the use of waste streams as substrates. However, in the current state of art, this technology has not yet achieved high productivity when waste streams are used as substrates due to their diluted nature; and this productivity must be high to achieve a sustainable production of PHA. Therefore, several technologies for increasing productivity have been proposed which may offer good opportunities but are still poorly applied and under study. Another major disadvantage in using MMCs is that extracting PHA from MMCs biomass is difficult. Despite this and the fact that pure culture technology of natural or engineered microbial strains to produce PHA is mainly used, the production of PHA by MMC is increasingly considered both for the possibility of reducing the costs of the process and for integrating the production of PHA. in the biological treatment of waste water and organic waste (Mannina et al., 2020).

In the second scenario, namely Scenario B, Rufí-Salís et al. (2020) analyzed the recovery of phosphorus from wastewater by precipitation of magnesium ammonium phosphate (MAP, with formula $NH_4MgPO_4{*}6H_2O$), namely struvite. It precipitates in a molar ratio of magnesium (Mg^{2+}), ammonium (NH_4^+) and phosphate (PO_4^{3-}) equal to 1:1:1, in suitable pH conditions (8.5–9.5) (Bouropoulos and Koutsoukos, 2000; Buchanan et al., 1994; Le Corre et al., 2009). Several recovery processes are then suggested implying different recovery efficiencies, chemical and energy requirements. Among these, the REM-NUT® process (Petruzzelli et al., 2004) can be considered a suitable option, although other options are also available, e.g. Ostara® and AirPrex® with competing performances (Rufí-Salís et al., 2020). This process encompasses ion exchange capable of recovering P in the form of MAP struvite from the treated secondary effluent. In this case, by adding Mg^{2+} to the stoichiometric ratio, the struvite is precipitated. Although this promising innovative process has several limitations, such as high economic costs compared to other recovery technologies, due to the need for resins and chemicals (Egle et al., 2015), the study was taken into consideration as possible scenario for Campania Region as it offers several advantages. From an environmental point of view, REM-NUT® allows to recover P, whose efficiency as a fertilizer is comparable to that of chemical fertilizers (Ye et al., 2020), thus offering a valid option to reduce the extraction of phosphorus from phosphate rock which is a finite, irreplaceable and non-renewable resource, which is supposed to be exhausted in less than 100 years (Daneshgar et al., 2018). Moreover, P recovery allows to further reduce eutrophication potential when wastewater ends up again in the water bodies. From an economic point of view, P removal allows to overcome an expensive and demanding maintenance problem that many WWTPs face (Sena et al., 2021). Further, struvite has a property that makes it interesting, namely it is a slow-release fertilizer; Last but not least, not only struvite precipitation allows the recovery of phosphorus but also of nitrogen: MAP precipitation can be regarded as an elegant method for ammonia disinhibition.

In the third scenario, namely Scenario C, Lin et al. (2016) evaluated the economic and environmental profiles of three alternative nitrogen removal and recovery technologies integrated into wastewater treatment systems, including conventional nitrification–denitrification, as well as Anammox and anaerobic ion exchange technologies. With the conventional technology of nitrification/denitrification, ammonia is first oxidized to nitrate and then, through an anaerobic step, nitrate is converted into a harmless nitrogen gas. Anammox technology, instead, consists in the partial oxidation of ammonia to nitrite, which acts as an electron acceptor in a reduction reaction, and is then converted to nitrogen gas under anoxic conditions. Moreover, ion exchange technology consists in removing and recovering impurities from the water. In this study, nitrogen resources is recovered through an anaerobic treatment with an anaerobic membrane bioreactor (AnMBR). In this case, the method involve a zeolite adsorbent because it is a low cost material with high cation-exchange ability and with molecular sieve properties, and contrary of conventional method, COD (Chemical Oxygen Demand) removal is achieved via anaerobic digestion occurring in the AnMBR. In particular, this pathway involves an AnMBR and a highly NH_4^+-selective ion exchanger unit with a Na-form clinoptilolite absorbent. After removing COD and filtering particulate matter, the anaerobic digester supernatant from the AnMBR flowed through the ion exchanger with NH_4^+ being adsorbed. While conventional technology is energy-intensive and produces large amounts of sludge and has no further benefits other than meeting the concentration limits of the effluents (Aubrey Beckinghausen et al., 2020). On the contrary, the other technologies seem to be very promising because they allow nitrogen to be removed and recovered with high efficiency. Moreover, Anammox technology requires less energy and oxygen, and does not need an external electron donor. Nevertheless, wastewater treatment through ion exchange process was chosen as Scenario C, as the study demonstrates that, with this technology, a larger amount of nitrogen is removed than conventional and Anammox technologies and it has a large potential to provide optimal economic and environmental performance through design and process optimization.

Finally, the fourth scenario, namely Scenario D, is built on a study by Soares et al. (2019) which describes the state of the art of wastewater treatment with microalgae, and their potential generation of electricity. In particular, the production of algal biomass through wastewater treatment is examined, which is subsequently used to produce biogas. The study is divided into two steps: first, the production of algal biomass is obtained using High Rate Algal Ponds (HRAP), i.e. an anaerobic treatment of wastewater and, second, the algal biomass is collected through coagulation-flocculation and then incorporated in a thermal conversion process, gasification, for the production of electricity in the form of biogas. Microalgae are well known to have a great ability to efficiently utilize nutrients from wastewater, as their cultivation requires high amounts of nitrogen and phosphorus. In addition to enabling efficient wastewater treatment, microalgae biomass is a potential source of valuable chemicals and other products, attracting wide interest lately (biodiesel, biopolymers, proteins) (Arashiro et al., 2020). In particular, microalgae have been recognized as a promising feedstock for biofuel production especially when their cultivation is combined with wastewater treatment as this combination can reduce CO_2 emissions and the cost of producing biofuels from microalgae (Chen et al., 2015).

3.3. *Water flows through water-demanding economic sectors*

The water flows assessed in the three economic sectors of the Campania Region are shown in Fig. 5. Out of the total volume withdrawn from freshwater sources, the household sector withdraws 968 Mm^3 of water. Of these, 84% is introduced into the public water distribution network while the remaining volume is partly lost and/or partly sent to other economic sectors. Out of all the water fed into the public network, only 53.3% is consumed by households (ISTAT - Istituto Nazionale di Statistica, 2017a).[2] Concerning wastewater generation, we cannot ignore, regretfully, that official data are fragmented and incomplete, which forces us to make several assumptions and estimates. As explained in Section 2.2. (Data sources use to estimate regional water flows) and shown in Figs. 5 and 67% of household use ends up as wastewater in the municipal wastewater network: in lack of official and reliable data, the estimate was based on performances of the main Campania Region sewage treatment plants (Section 2 and Table 4), compared to similar systems in Emilia Romagna region. Looking at the estimation in the household sector, it is possible to conclude that the volume withdrawn for this sector is rather large, as it corresponds to 52.7% of the total volume withdrawn from water sources. According to ISTAT- Istituto Nazionale di Statistica (2020), Campania Region was one of the regions

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[2] According to ISTAT, 2017: "… *È evidence che meno della metà del volume di acqua prelevata alla fonte non raggiunge gli utenti finali, a causa delle perdite idriche dalle reti di adduzione (tra il punto di prelievo e il serbatoio) e reti di distribuzione (tra i volumi immessi in rete e quelli erogati agli utenti finali). I volumi di acqua persi dalle reti di adduzione, …, ritornano in natura e rialimentano il corpo idrico; mentre, i volumi persi nelle reti di distribuzione sono la componente più critica e prevalente, poiché si tratta di acqua sottoposta a trattamenti di potabilizzazione, dispersa lungo la rete e non più utilizzabile* …". Although this clarification is also provided in English within the present Section 3.1, we felt important to make explicit reference to the official document, where large part of the losses is attributed to the degraded status of both adduction and distribution lines.

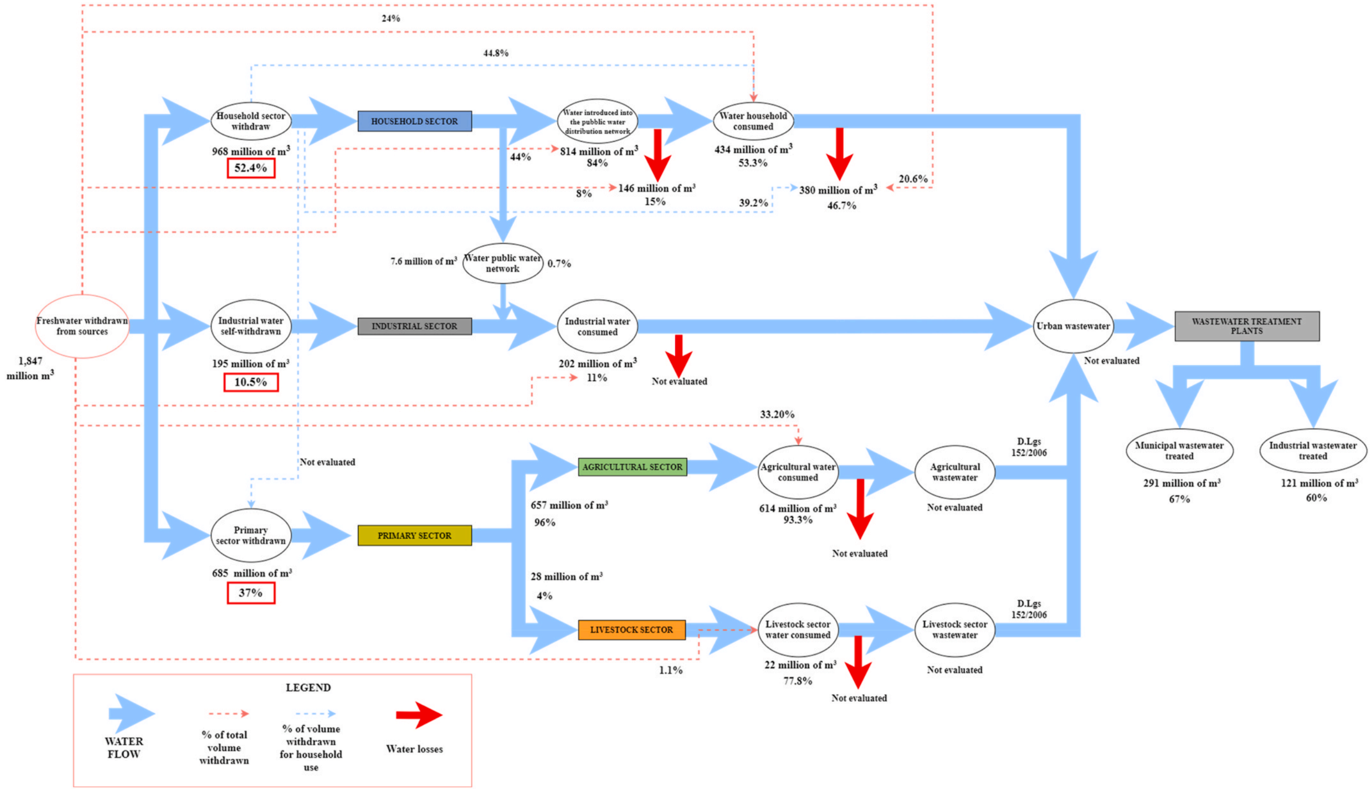

Fig. 5. Flowchart of water flows in household use, industrial and primary sector in the Campania Region.

where the highest amount of water withdrawn for household was recorded, corresponding to 10% of the total national withdrawal. Furthermore, compared to the total volume of water withdrawn for household use, only 44.8% reaches the final users and is therefore consumed. This is caused by water losses over the adduction networks and distribution networks. While water lost by supply networks, in most cases, return to nature to re-fill water bodies, water lost in the distribution networks are the most critical part, since it is water subjected to potabilization treatments, dispersed along the network and no longer useable. These losses can be physiological and related to the extension of the network, the number of connections, their density and operating pressure; or, due to various factors, such as broken pipes, unauthorized consumption, abusive withdrawals from the network, meter measurement errors (ISTAT - Istituto Nazionale di Statistica, 2019).

In the case of the industrial sector, from the estimates of the water consumed (which, in the absence of reliable data, were assimilated to withdrawn water), it emerges that this sector receives a small amount of water from public water distribution network, equaling about 0.7% of the total volume withdrawn from the household sector, and an amount equal to 10.5% of the total volume of freshwater withdrawn from the sources. Summing-up the two contributions, industrial sector consumes around 11% of the total withdrawn water. It can be concluded that only a tiny portion of the withdrawn water is allocated to industrial sector in Campania Region. Overall, industrial wastewater represents 60% of the volume consumed by manufacturing industries. This percentage includes wastewater attributable to the consumption of employees (toilets, hand washing, canteens, etc.) and wastewater attributable to the various uses of water relating to industrial processes (process water, washing machinery, etc.).

The primary sector withdraws 685 Mm^3 from the water sources, accounting for nearly 37% of the total volume withdrawn from the sources. Of this, 657 Mm^3 (96%) are allocated to agriculture which consumes 94% of the total volume, and 28 M m^3 for livestock sector.

Fig. 6 shows the percentages of water consumed by the 3 main sectors in Campania Region. Considering the total water consumption in the analyzed sectors, it results that 48.2% is consumed by the agricultural sector. This confirms the important role of the agricultural sector as the main consumer of water and, at the same time, as also the main source of water pollution from eutrophicating substances. In fact, in Italy, the percentage of water consumption for irrigation purposes reaches up to 60% on average, falling slightly in the Hydrographic District of the Southern Apennines, a district with a deep agricultural vocation (Distretto Idrografico dell'Appennino Meridionale, 2016).

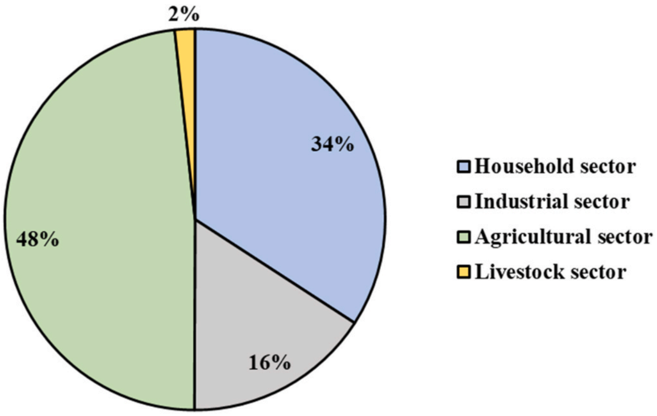

Fig. 6. Water consumption estimated for the economic sectors in Campania Region.

With regards to the estimations of wastewater to be treated, agricultural and livestock wastewater were not evaluated, as they are mainly assimilated to municipal wastewater according to Art. 101 of Legislative Decree 152/2006 (Repubblica Italiana, 2006). Taking as a reference year 2018, a theoretical volume of 411 Mm^3 of wastewater treated was estimated, corresponding to 64.6% of water consumed by the household and industrial sectors together and, of which 67% of municipal wastewater and 60% of industrial wastewater. Data on the state of the wastewater plants in the Campania Region are also fragmented and outdated; in addition, some of them are currently undergoing renovation and expansion. However, in a 2003 study on the evaluation of the purification efficiency of the urban wastewater treatment plants of Campania Region, (Avallone et al. (2003)) showed, through the chemical characterization of the treated wastewater, that the analyzed infrastructures (the same considered in this study) receive the majority of municipal wastewater (to confirm the percentage of 67%).

3.4. Current state of wastewater treatment in Campania Region

In order to understand the current state of wastewater management in Campania Region, an analysis of the census of the wastewater treatment plants in Campania Region (ARPAC - Agenzia Regionale per la Protezione Ambientale in Campania, 2020) was carried out. Fig. 7 shows a diagram of the current plants and related types of treatments. As shown in the figure, most of the wastewater is treated by mechanical and microbiological treatment, mostly conventional biological treatment with activated sludge. This means that pollutants are removed by screening, settlement and filtration, while the dissolved fraction of pollutant is removed by microorganisms present in the sludge. In particular, the treatment of biologically-activated sludge is then followed by anaerobic stabilization (anaerobic digestion) of the primary and secondary sludge, with the aim of reducing the amount of produced sludge and degrading its organic substance, and, subsequently, by a final disinfection with sodium hypochlorite. This type of treatment has been confirmed by Braga and Polverini (2018) in their reporting for the parliamentary inquiry regarding waste management in Campania Region. However, in all the plants, during the management prior to 2012, anaerobic digestion processes were interrupted, due to the fact that most of the plants were oversized compared to the water treated, which made the available sludge insufficient to a profitable AD within each plant. This, consequently, translated into a large production of untreated sludge in the Region, aggravating costs and leading, up to now, to the need for maintenance and re-functionalization of the plants, in compliance of the limits imposed by current legislation on wastewater (Braga and Polverini, 2018).

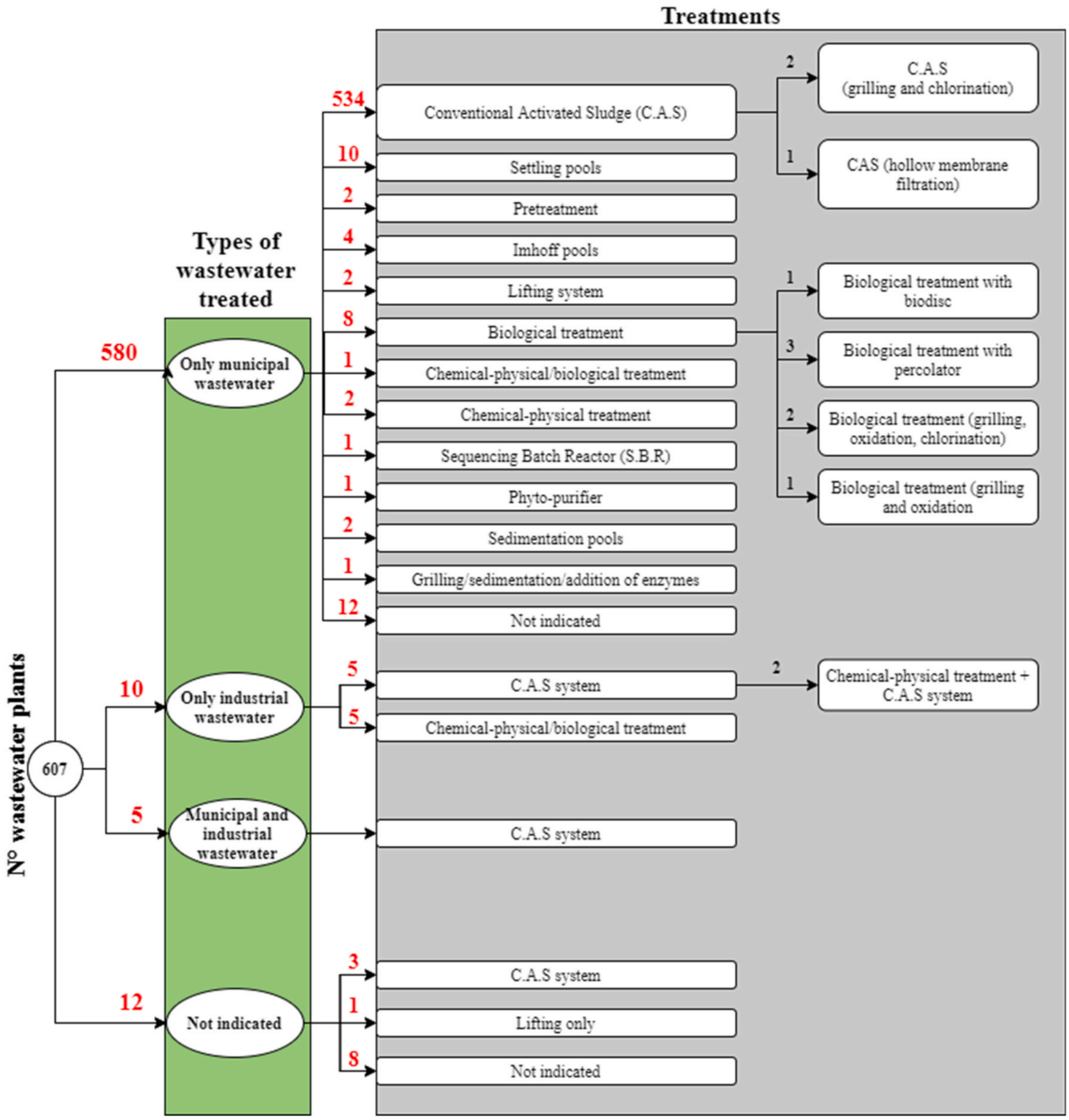

Fig. 7. Census of wastewater treatment plants in Campania Region. Data source: ARPAC - Agenzia Regionale per la Protezione Ambientale in Campania (2020).

3.5. Economic, technological and environmental scenarios of proposed circular pathways, at the local scale of campania region

In order to evaluate the possibilities of circularity of the wastewater sector, scenarios A, B, C and D described above can be tested against the real data of Campania region to explore performances and results (Fig. 8). The same procedure can be applied elsewhere, after careful examination of local data.

The application of Scenario A shows that in Campania Region it is possible to recover 47,340 tons of PHA from potentially treated wastewater (Table 5). In the study of Roibás-Rozas et al. (2020) is indicated that for each kg of PHA, 0.72 kg of PET would be avoided; therefore, a total production of 61,583 tons of PET would be avoided in Campania Region. Since the total production of plastic in 2018 equaled 138,866.8 tons of PET (ISPRA, 2018), the recovery of PHA from wastewater would allow a total saving of 44% of the production PET.

By applying Scenario B, 1179 tons of struvite from Campania wastewater would be recovered. This means that, since the amount of phosphate fertilizers distributed in 2018 was equal to 2455 tons (ISTAT - Istituto Nazionale di Statistica, 2018c), the application of scenario B would allow a saving of 48% of the P fertilizers currently distributed in Campania Region.

With application of Scenario C it is possible to recover 24,666.8 tons of nitrogen from Campania Region wastewater. Consequently, considering the distribution of nitrogen fertilizers in 2018 amounted to 44,862 tons (ISTAT - Istituto Nazionale di Statistica, 2018c)), the recovery of nitrogen would allow a saving of 54,9% of the N fertilizers currently distributed in Campania Region.

Finally, the application of scenario D to the context of Campania Region would supply 117,853 tons of algal biomass. From the statistical data on electricity in Italy, 16,778.7 GWh of electricity were consumed in Campania in 2018 (Terna SpA, 2018). As highlighted by Soares et al. (2019), which shows the corresponding electricity production value equal to 0.83 kWh/kg of algal biomass, it appears that in Campania it would be possible to obtain a saving of approximately 1% of the total consumed electricity in the region. Although the percentage of electricity is low, there are still both environmental and economic benefits due to the recovery of wastewater no longer considered as waste and to the production of electricity from renewable sources, avoiding the consumption of fossil fuels.

Summarizing, both circular pathways showed a twofold advantage: avoiding the disposal of wastewater and therefore the detrimental burdens it implies and, at the same time, recovering resources with high added value.

In particular, PHAs are among the most promising potential substitutes for conventional non-biodegradable plastics thanks to their physicochemical properties and advantages, such as:

- biodegradability to solve the problem of with the required time and environment needed for the petroleum-derived plastic to break down;
- reduction of operating costs waste management, especially if used on a large scale;
- lower emissions of toxic fumes in case of incineration.

Furthermore, the environmental and economic performance of PHA production can be improved if integrated into already existing plants (WWTP, biodiesel plants, hydrogen production factories) or by combining the production of different by-products, such as biogas or compost. However, there are only a few pilot-scale plants operating

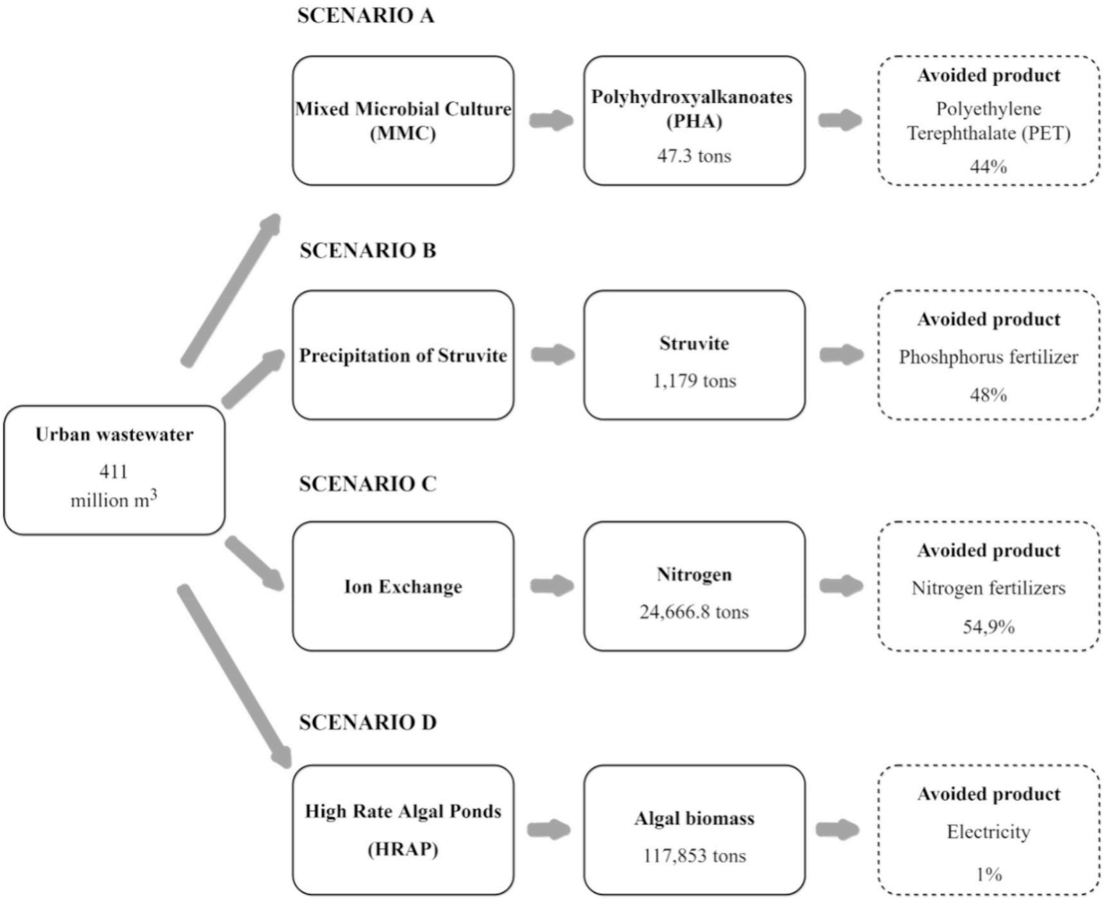

Fig. 8. Potentially recovered by–products from Campania Region's wastewater and avoidable industrial products.

worldwide for the production of PHA from wastewater (Mannina et al., 2020) and scientific studies are still scarce to have a comprehensive picture of the viability of the process. Nevertheless, being renewable does not necessarily imply being strongly sustainable (from an environmental, economic and social points of view), therefore further studies are needed. In addition, the recent European Disposable Plastics Directive (European Parliament, 2019), which will come into force by 2021, will also increase the pressure for a full ban on conventional polymers. In this context, the replacement of non-biodegradable fossil-based polymers with bio-based biodegradable biopolymers could have significant advantages such as a drastic reduction of plastic pollution in the environment.

The recovery of phosphorus from wastewater in the form of struvite in Campania Region could be a valid alternative to the use of chemical fertilizers to reduce the impacts they cause, but also to bring economic benefits. In a recent study, Muys et al. (2020) shows that struvite is currently marketed at prices below the estimated market value of its macronutrients. However, the use of struvite as a fertilizer is a method that is still not very widespread in Italy as it is not specifically regulated and therefore some administrations still consider it a “waste” rather than a “by-product”. However, on October 24, 2017, thanks to a series of amendments to the European Fertilizer Directive, struvite is among the fertilizers with the CE marking (European Parliament, 2017). Furthermore, the recovery of local phosphorus could also improve the metabolism of urban areas through the circulation of resources, as urban and suburban areas are hot spots of wastewater production. However, there is a potential concern that, in some cases, the environmental impacts created by the recovery of struvite through the use of additional chemicals and energy could offset its benefits. For these reasons, further studies are necessary to assess the environmental impacts associated with the recovery process of struvite in wastewater treatment plants (Sena et al., 2021).

Nitrogen is essential for all living beings. As a synthetic fertilizer, it has been supporting food production for years, but at the same time it is harmful to the environment. In fact, it can have impacts on atmospheric pollution, soil acidification, biodiversity loss and water eutrophication. Sources of anthropogenic nitrogen have increased with increasing population and human activity and the main sources of ammonia or nitrogen come from urban wastewater and, to a greater extent, from industrial wastewater effluents (e.g. production of fertilizers, ceramics and cement factories, oil refining and combustion processes) (EL-Bourawi et al., 2007). Considering the growing sources of anthropogenic nitrogen, research has begun to shift attention to nutrient recovery involving nitrogen in addition to phosphorus, not only to prevent eutrophication, but also to save energy and natural resources (Aubrey Beckinghausen et al., 2020). The recovery of nitrogen, as well as that of phosphorus, can be an alternative to replacing chemical fertilizers while, at the same time, also allowing a reduction in wastewater treatment costs.

As widely recognized, current energy systems not only put pressure on depleting resources, but also lead to increased greenhouse gas emissions, especially CO_2. Microalgae are a potential source of biomass for the production of biofuels for energy generation. They can produce energy-rich substances such as lipids for the production of biodiesel and biogases (hydrogen, methane, carbon monoxide). Furthermore, algal biomass can be used as a feedstock for the generation of numerous high-value bioactive compounds that can be used as pharmaceutical compounds, health foods and natural pigments (Suganya et al., 2016), such as fatty acids (linoleic acid), carotenoids, sterols, phycobiliproteins or products such as food supplements, fish feed. The use of microalgae for biofuel production is advantageous as microalgae do not require arable land for cultivation, have a high activity of photosynthesis and bioaccumulation efficiency and a high rate of biomass productivity compared to other organisms (Goswami et al., 2020). However, the highest energy demand of the entire production system occurs in the recovery phase of microalgae biomass and the economic cost of recovery accounts 30% of the total cost of biomass production. Therefore, the cultivation of microalgae for biofuel production is not yet economically viable and the industry’s biggest challenge is the development of economically-sound recovery methods (Soares et al., 2019). Finally, microalgae can be grown in wastewater as they can degrade organic pollutants and produce biomass (Matamoros and Rodríguez, 2016). In particular, they have a high potential to remove nutrients from wastewater that they simultaneously use as sources of carbon and nutrients (Chen et al., 2015). Therefore, treating wastewater with microalgae is advantageous because, on the one hand, the obtained algal biomass can be used for the production of bioproducts or biofuels and, on the other hand, the cleaner wastewater can be furtherly reused thus saving freshwater to be withdrawn (UNESCO, 2017) and energy to be consumed for the treatment and distribution of water. There are many examples of water recycling in the wastewater sector. In particular, the Italian Legislative Decree 152/2006 (Repubblica Italiana, 2006) suggests that recycled water can be used for irrigation purposes, urban uses (street washing, heating and cooling, sanitary uses) and industrial uses.

As previously said, the majority of the innovative technologies found in literature are still at pilot scale, therefore, the applicability on large scale as well as their environmental performance represent future frontiers of research needed to compare conventional wastewater treatment options with potential resource/energy circular options and to eventually identify improvement opportunities (Hao et al., 2019). In particular, circular economy patterns and scenarios not only can be usefully implemented in developed areas affected by heavy population and agro–industrial density, but can also translate into suitable tools in developing countries, affected by large amounts of untreated wastewater as well as large demand for energy, fertilizers, biochemicals and organic products, recoverable from appropriate wastewater treatment.

4. Conclusion

Wastewater management is of considerable importance to meet the increased demand for water and resources while also tackling the need for safely treating the growing amount of wastewater, especially in densely populated urban areas with poor wastewater management. In this study, four alternative circular pathways were hypothesized, stemming from an extensive review of scientific literature. All the four scenarios showed that recovering high-value products from wastewater treatment may have a twofold advantage: in addition to bioremediate wastewater – thus lowering the environmental impacts of a harmful waste –, it also prevents further freshwater withdrawals while providing a small but non-negligible fraction of renewable energy to society. Finally, testing the four scenarios against the use of water as well as potential production of treatment co–products in Campania Region provides a tool to understand the applicability of the same processes elsewhere in Europe and worldwide.

CRediT author statement

M. Colella: Data curation, Writing- Original draft preparation M. Ripa: Conceptualization, Methodology, Data curation, Writing- Original draft preparation. A. Cocozza: Writing- Reviewing and Editing. C. Panfilo: Writing- Reviewing and Editing. S. Ulgiati: Conceptualization, Writing- Reviewing and Editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113171.

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