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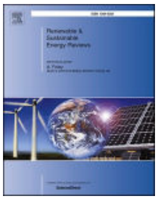

A transition from conventional irrigation to fertigation with reclaimed wastewater: Prospects and challenges

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ABSTRACT

The aim of this review was to discuss the transition from traditional irrigation to fertigation using reclaimed wastewater in countries with moderate climate. In most European countries there are no regulations on waste water reuse and on the other hand there are countries where regulations are very strict. An important aspect is to standardize the restrictions, which would minimize uncontrolled use of wastewater for fertigation. Wastewater is a source of plant nutrients and organic matter, but can be contaminated with chemicals and pathogens, which in turn can lead to secondary environmental pollution. The reuse of recovered wastewater may require modification of the wastewater treatment process line or construction of stabilization tanks at farms. In both cases, it is necessary to set up initial installations in real systems in order to develop principles for irrigation with reclaimed wastewater for soil and temperate climate conditions. The additional treatment steps required are also associated with large investments, but could reduce fertilization costs and, more importantly, improve the environmental situation. The current scale of fertilizer application does not allow conventional fertilization to fulfill global demand. The introduction of such a solution is a step towards the practical application of circular economy and sustainable crop production. The paper discusses a challenges related with implementation of transition from conventional irrigation to fertigation with reclaimed wastewater in moderate climate countries. A special focus to providing fertilizer nutrients in terms of required doses was undertaken.

1. Introduction

According to the Food and Agriculture Organisation of the United Nations (FAO), energy-food-water nexus are combined together. Sustainable energy and food supply is the most important issue today [1]. We need to acquire these resources without depriving future generations [2]. Water security is linked with energy and food security, all of which are endangered by the consequences of climate change. Among the United Nations' Sustainable Development Goals (SDGs), the water scarcity caused by warming is highlighted in climate action or clean water and sanitation. The scarcity of water is the part of abiotic stress that has a substantial impact on plant growth. In particular this concerns moderate climate, where plants have acclimated to abundant water conditions. Due to the recent climatic changes, now agricultural plantations in moderate climate suffer from water scarcity. The solution would be to either modify the plants cultivation profile or to provide additional water by e.g. using treated wastewater.

Human activity affects the warming of the climate, which directly results in the acceleration of the hydrological cycle not only regionally, but also on a global scale. In this situation the amount of rainfall, may change. In many parts of the world numerous weather anomalies, including the trend in decreasing precipitation was observed [3]. Social and economic development is strongly dependent on the availability of water: it is estimated that demand for water may increase by 30% by 2040. The situation is similar with energy consumption: even a 40% increase is predicted within that time. Research on water-energy nexus is necessary to take into account all the interdependencies of the two most important areas [4].

Abbreviations: AOP, Advanced Oxidation Processes; BOD, Biochemical Oxygen Demand; CFU, Colony-forming Unit; COD, Chemical Oxygen Demand; EDO, European Drought Observatory; EU, European Union; FAO, Food and Agriculture Organisation; NPK, nitrogen, phosphorus, and potassium; IFA, International Fertilizer Industry Association; PDSI, Palmer Drought Severity Index; SPI, Standardized Precipitation Index; RDI, Regulated Deficit Irrigation; SDCI, Drought Condition Index; SDG, Sustainability Development Goals; UV, ultraviolet; WHO, World Health Organization.

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Drought is considered one of the most dangerous natural hazards. It is the direct cause of serious environmental problems and triggers economic consequences [5]. The search for solutions enabling the use of marginal water sources for social purposes in the period of reduced rainfall is continuing. One of the proposals is to use the potential of treated wastewater for irrigation of agricultural areas. Hybrid wastewater treatment systems can also recover energy from wastewater, in particular from organic pollutants, which complements environmentally friendly energy management [6].

The consequence of climate warming is hydrological drought and resulting reduction of freshwater availability, also in the region of temperate climate that did not experience water shortage problems in the past. The consequence of drought is dry soils and significantly lower crop yields. For many Western and Central European countries that are specialized in food production (Germany, France, Poland) deficiency in water already raised food prices, which are agricultural products. Treated wastewater could be considered as a valuable resource, instead of a waste, although wastewater reuse may cause both health and environmental hazards. Irrigation with treated sewage is already practiced in/by high-income countries with semi-arid land: France, Italy, Spain, Cyprus, Malta, Israel, Jordan or the USA [7]. In the countries with moderate climate (e.g. Poland, Germany) it has not been implemented yet.

The quantity of fertilizer nutrients removed by the crops from the previous vegetation season must be replenished and water needs to be permanently supplied. The fertilizers with a lower environmental impact are recommended as a substitute for conventional fertilizers [8]. The solution could be the use of partially treated wastewater that is not directed to tertiary treatment, which means containing what is called – biogenic compounds (N and P). According to IFA, during the last half of the century the consumption of fertilizers increased six times [9].

The concept of wastewater reclaiming by fertigation is not new. The use of sewage for irrigation of fields has been known since ancient times. Already prehistoric Egyptians, Minoans and Indians used the potential of the wastewater for agricultural purposes. The first pioneers in wastewater recycling for irrigation were undoubtedly the Minoans, as evidenced by the collection systems for waste- and rainwater in Crete's palaces [10], where the first wastewater sanitary installation was built. Partially treated water that flowed through the sewerage was used to fertigate agricultural fields. Nowadays because of a large scale, strict law regulations are required to prevent any sanitary-epidemiological danger.

In modern biological wastewater treatment plants, sewage goes through preliminary, primary, and secondary treatment where the majority of suspended solids and organic pollutants (expressed as BOD and COD) are being removed. Treated municipal wastewater – secondary effluents can become an alternative source of water, as well as nutrients to meet the needs of cultivated crops. After secondary treatment, sewage is transferred to tertiary treatment of biogenic compounds removal consisting of denitrification, nitrification and dephosphatation tanks where nitrogen and phosphorus are removed. In tertiary treatment, also known as biogenic compounds (N, P) removal, nitrification, denitrification and dephosphatation are employed to reduce the load of N and P compounds that are fertilizer nutrients in their own right. Tertiary biogenic treatment will not be necessary if water is to be used for fertigation/irrigation purposes. This will call for effluents sanitation and building water distribution systems that could transport it from the treatment plant to the agricultural fields. If partially treated sewage is to be used for fertigation, tertiary treatment can be omitted, and wastewater could be directed through disinfection and correction of composition to agricultural fields. Irrigation with treated wastewater has a positive and negative environmental impact. There are many risks related with agricultural wastewater re-use like presence of microbial pathogens, content of micropollutants and higher salinity of the soil [11].

Recently, wastewater recycling in agriculture has become a significant part of water supply in agriculture in countries of the Mediterranean climate [12]. The additional benefit is the preservation of drinking water resources and lower environmental impact related to the discharge of waste water into surface waters. The presence of N, P, K and organic matter in treated effluents additionally maintains soil fertility and productivity, improving crop yield and reducing fertilizers application rates. The least energy-intensive way to recover water is to produce it from wastewater [13]. The absence of a third stage of wastewater treatment is an additional energy benefit.

Contrary to other review papers, the present manuscript discusses a transition from conventional irrigation to fertigation with reclaimed wastewater in moderate climate countries. A special focus to providing fertilizer nutrients in terms of required doses was undertaken. Prospects and challenges in practical implementation of fertigation was discussed.

2. New challenges of climate change

The hydrological drought is the result of atmospheric drought, the period during which flows in rivers fall below the long-term average values. In the case of prolonged drought, there is a significant reduction in surface water and groundwater resources supplying the rivers in the period without rainfall. Drought can also be exacerbated by human activity [14].

To track the phenomenon of drought, various techniques can be used, including the standardized precipitation index (SPI), Palmer drought severity index (PDSI), drought condition index (SDCI) and others. All methods are based on the observation of characteristic hydroclimatic parameters that change over time and space [15]. Satellite images enable precipitation monitoring, soil moisture and plant health, as an early warning system against drought. The integration of various hydroclimatic variables or indicators, i.e. precipitation, soil moisture, evapotranspiration, and vegetation from different areas enables effective drought monitoring. Drought tracking combines *in situ* observations, the use of remote sensing products, simulations of land surface models and climate predictions [16].

Weather disturbances can cause local and global changes, contributing to many negative effects, such as lower yield quality and consequent socio-economic changes [17]. The area of land covered by drought is expanding from year to year. It is estimated that it will increase from 1% to 30% in the 21st century [18]. Over the past 30 years, drought has caused losses of over 100 billion euros in EU and has covered almost 40% of Europe's area [19].

Fig. 1 presents the Food and Agriculture Organization of the United Nations (FAO) and the European Drought Observatory (EDO) data illustrating temperature changes and the annual average rainfall for selected European countries in the years 2014–2019. The Mediterranean countries are the most affected by drought and are described as the 'hotspot for climate change in Europe' [20]. Despite a moderate climate, central European countries (Germany, Poland, Czechia) are exposed to drought. Since 2000, the greatest climatic changes have been observed in these areas, which manifested itself in a large increase in temperatures and a decrease in precipitation. Droughts were most common in spring and summer, but the trend has changed over the last 20 years and EU countries are already struggling even with winter droughts [21]. In the future, climate change will lead to increased drought in Central Europe and the Mediterranean countries. The projected situation will pose a particular threat to agriculture and water resources in these areas [19].

Drought is a regional phenomenon and means continuous limited availability of water, below the average value in natural conditions [24]. Drought covers all disadvantageous phenomena related to water scarcity for a given region. The main sectors that are affected by drought are agriculture, energy and industry as well as water quality [19]. Low water levels during hydrological drought increase the residence time of water in reservoirs, reducing their rinsing, and thus affecting water quality [25]. Drought occurrence may consequently cause soil drying

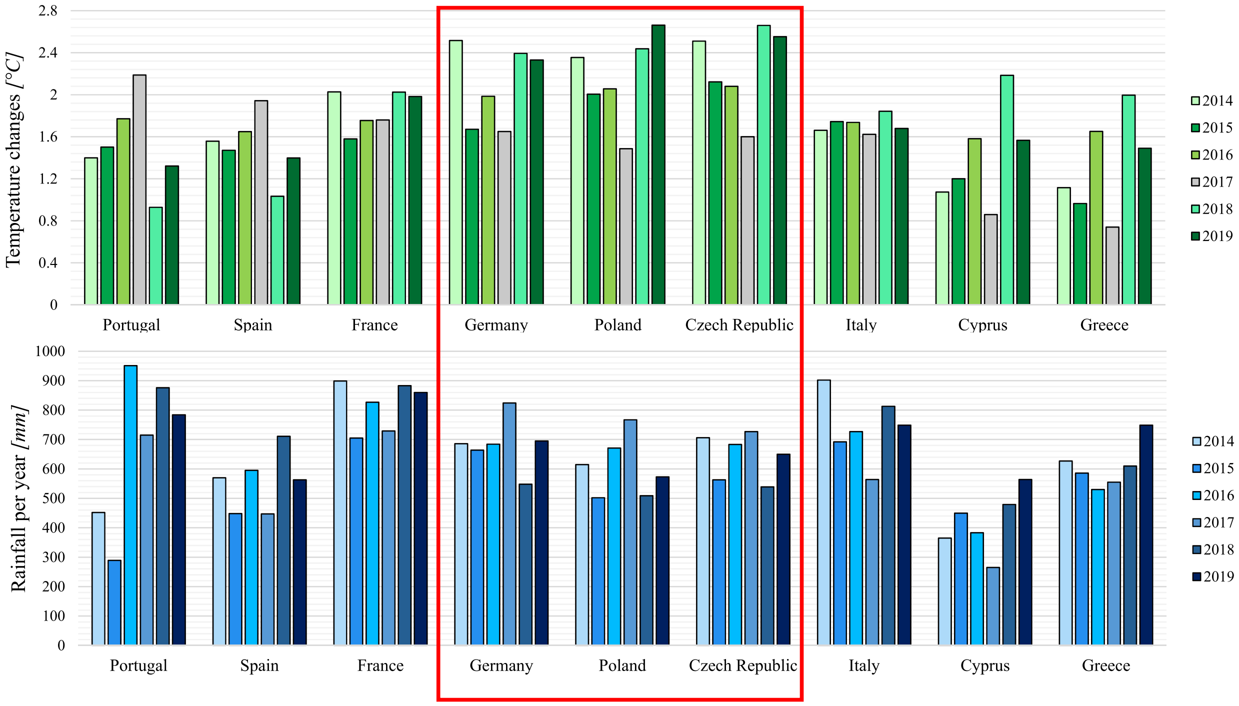

Fig. 1. Temperature changes (a) and annual average rainfall (b) for selected European countries in 2014–2019 [22,23].

and reduction or complete destruction of plant crops. Agricultural drought is a direct consequence of hydrological drought. During this time the plants do not receive proper hydration and thus all components necessary for plant growth (i.e. macro- and micronutrients). Other negative effects include not only crop losses, but also increased risk of fires, soil degradation and social changes caused by increased competition for resources [18].

Many semi-arid and arid areas are struggling with water shortages, this phenomenon is starting to appear more and more often in other areas, which so far have not had such problems. Apart from rainfall, agriculture must also take into account other forms of water supply to plants.

In areas susceptible to drought, the growth of plants with the forecast climate changes, including the prediction of drought, should be synchronized. As an example, the development of early maturing varieties can be given [26]. Under water scarcity conditions it is important to have sustainable irrigation management, including precise deficit irrigation (PDI) while controlling soil irrigation status. This has been applied to early maturing nectarine trees, which are extremely sensitive to water scarcity, especially in dry and hot periods [27]. Monitoring of soil irrigation has also had a positive effect on the growth and yielding of peaches [28]. Delayed planting of early maturing plants (e.g. potatoes) can also mitigate the effects of climate change and maintain proper crop yields [29]. Similar conclusions have been drawn for the population of early matured winter wheat [30].

Negative effects of drought on plant vegetation can be combated by artificial irrigation. The need for irrigation of crops significantly increases investment costs and may influence crop prices. It is estimated that agriculture uses up to 70% of global water consumption. In many regions of the world, irrigation is carried out in a non-economic way, using a significant excess of water. Irrigation should be carried out in accordance with procedures, including constant measurements of evapotranspiration and soil water tension [26]. To ensure that the plants have enough water to grow, and at the same time not cause wastage, special irrigation protocols are introduced and special technologies applied. The use of drip irrigation with low pressure saves up to 40% of water without affecting the quality of the yield [26].

Also, the concept of regulated deficit irrigation (RDI), which determines irrigation carried out using less water than the plant needs, is introduced. A small water scarcity may to some extent have a positive effect on plant growth and at the same time allow for water savings [31]. The response to stress caused by RDI changes depending on the plant growth phase. Furthermore, this reaction is influenced by additional factors, such as weather conditions or plant species [31].

The use of rainwater for supplemental irrigation can contribute to sustainable agriculture, allowing for overcoming not only drought but also soil erosion. Storage of rainwater at the time of conditions requiring additional irrigation enhances the interaction of environmental resources (rainwater) and satisfies the needs of the environment (the plant needs water).

Incorrect irrigation can lead to disastrous consequences. Water used in agriculture is often rich in salts that remain in the soil as a result of water evaporation. Increased concentration of salt may lead to soil salinity, causing its degradation.

Climate models predict a significant drop in rainfall and extended periods of drought in many areas, including the Mediterranean. At the same time, a significant increase in agricultural production is expected due to the rapid population growth [32]. In areas with a dry climate, field irrigation requires up to 85% of the available water resources, which enforces an effective use of water. Reduced access to surface or groundwater requires the use of other sources.

Global fertilizer demand is predicted to increase significantly reaching 202 million Mg in 2020. Demand for basic nutrients (nitrogen, phosphorus and potassium) will increase on average by 1.5, 2.2 and 2.4% from 2015 to 2020 annually (FAO).

Improper fertilizer management causes environmental and economic problems. When used in inappropriate amounts, proportions or terms, it may disturb proper functioning of the soil. Over-fertilization is typical for highly developed countries. The use of nutrients in excess of plant requirements may lead to changes in the ionic balance of soil solution and cause the migration of fertilizer nutrients into groundwater. If fertilizers are used inadequately, they may cause irreversible changes in the soil structure, including acidification, heavy metals accumulation or soil microflora disorder. Minerals introduced into soil in the form of fertilizers are not fully utilized during vegetation. Increased fertilization levels may lead to uneven use of minerals and serious environmental impacts. The only way to counteract unfavorable phenomena is to change fertilizer management [33]. A practical solution is the direct introduction of fertilizer components into the reclaimed water stream used for crops irrigation, called fertigation.

Fertigation is the application of a fertilizer solution with drip irrigation. This form facilitates the supply of water and nutrients directly to the root zone. Fertigation is a method that allows increased nutrient transport to the plant by precise supply of nutrients near the plant root system. The nutrients should be delivered in a controlled manner, depending on the weather. The advantages of fertigation are precision and uniformity of fertilization, and the fact that small doses of ingredients can be easily supplied to large areas [34]. Fertilizer doses are also considerably reduced because they can find multiple applications in smaller quantities. The possibility of precise selection of fertilizer doses allows for a quick response to the changing needs of plants, which makes this method also very economical. The nutrients are delivered in doses that can be used immediately by the plants. The migration of nutrients to deeper layers of soil or groundwater decreases [35]. The nutrients are delivered directly to the root zone, which greatly reduces nutrient losses to the environment. This solution fits the scope of precision agriculture.

The use of fertigation decreases the need for fertilizer and water (up to 25%), contributes to more efficient absorption of components by plants resulting in better productivity [36]. This saves water, nutrients and prevents leaching of nutrients from the soil into groundwater.

3. Fertigation with treated wastewater – benefits and problems

The use of fertigation is a way to use nutrients, in particular biogenic compounds of nitrogen and phosphorus (Fig. 2.). The presence of NPK (nitrogen, phosphorus, and potassium) in the secondary effluent serves as a fertilizer which is rich in major macronutrients (such as nitrogen, phosphorus and potassium) necessary for plant growth [37].

Table 1a presents the concentration of macroelements (NPK) in treated wastewater in different countries and in the various regions of a given country. The concentration of nutrients in pre-treated wastewater is dependent on the water management policies and on the systems used for wastewater treatment. The concentration of macroelements in pre-treated wastewater also varies for different regions. In different parts of Italy, the content of total nitrogen can vary up to about 100 times. Similar observations apply to both phosphorus, with the lowest value of 0.055 and mg/L and the highest value of 8.58 mg/L. Definitely, smaller fluctuations can be observed in potassium concentrations where the values are doubled at a maximum. The reuse of macro- but also micronutrients in regions where their concentrations reaches high values could significantly reduce the application rates of traditional fertilizers. However, considering the variable nutrient concentrations in treated wastewater, permament monitoring is necessary. In order to ensure that plants receive an appropriate dose of nutrients, a correction in composition should also be considered, including the possible addition of supplementary doses of fertilizers to the water for fertigation for composition correction purposes, to satisfy crop nutrient requirements.

Biological processes are the main methods used to eliminate phosphorus and nitrogen from sewage. These processes allow the elimination of most nutrients. However, secondary effluents from municipal wastewater treatment plants contain nitrogen and phosphorus, whereas domestic secondary effluents contain 5–30mgL^{-1} of total nitrogen and 0.2–3mgL^{-1} of total phosphorus [53]. Assuming an application rate of 5000 m^3/ha·year, it is possible to use 25–150 kg/ha·year and 1–15 kg/ha·year of nitrogen and phosphorus from the wastewater, respectively [54].

Assuming the use of 5000 m^3/ha·year of wastewater and the load of macroelements in pre-treated wastewater in selected countries and regions, the possibility of replacing traditional NPK fertilizers (Table 1b) with treated wastewater was calculated. For calculations the assumed demand for macroelements for maize was 130 kg/ha·year, 15.5 kg/ha·year and 19.5 kg/ha·year of nitrogen, phosphorus and potassium, respectively [55]. In most countries, the use of treated wastewater would allow for 100% coverage of both phosphorus and potassium demand. In all regions of Brazil, but also in Saudi Arabia or Poland, the nitrogen loads of the wastewater would cover the total demand for this macroelements. The situation is slightly different, e.g. in Greece, where only about 25% of the nitrogen from sewage could replace that applied

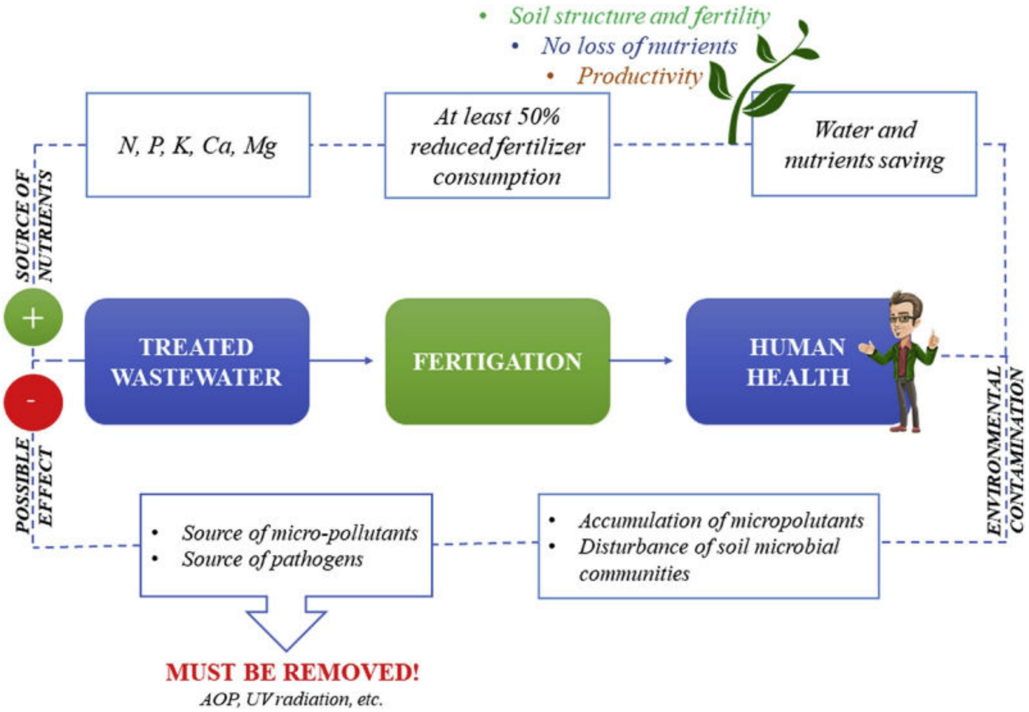

Fig. 2. Fertigation scheme – possible benefits and drawbacks.

Table 1a
NPK macroelements content in pre-treated wastewater.

	Nitrogen			Phosphorus			Potassium	References
	mg L^{-1}			mg L^{-1}			mg L^{-1}	
	Amount/Type		Total	Amount/Type		Total	Total	
Israel	4.80	*NH_4*	**19.9**	5.80	*Total*	**5.80**	**29.6**	[38]
	15.2	*NO_3*						
	19.9	*Total*						
Israel	20.2	*Total*	**20.2**	5.56	*Total*	**5.56**	**31.2**	[39]
Jordan	169	*NO_3*	**62.6**	n.a.	n.a.	n.a.	**n.a.**	[40]
	80.3	*NO_2*						
Italy	27.7	*Total*	**27.7**	6.40	*PO_4*	**2.08**	**n.a.**	[41]
Italy	0.0400	*NH_4*	**6.61**	0.290	*PO_4*	**0.0940**	**9.35**	[42]
	29.1	*NO_3*						
	0.0200	*NO_2*						
Italy	0.0400	*NH_4*	**6.57**	0.170	*PO_4*	**0.0550**	**9.35**	[43]
	29.1	*NO_3*						
Italy	3.00	*NO_3*	**0.670**	25.0	*PO_4*	**8.58**	**23.0**	[44]
Greece	42.0	*Total*	**42.0**	4.00	*Total*	**4.00**	**n.a.**	[45]
Brazil	50.5	*Total*	**50.5**	8.82	*Total*	**8.82**	**37.7**	[46]
Brazil	–	-	–	0.470	*Total*	**0.470**	**2.31**	[47]
Brazil	47.6	*Total*	**47.6**	8.21	*Total*	**8.21**	**33.9**	[48]
	35.7	*NH_4*						
	10.8	*Organic*						
	1.08	*NO_3*						
Pakistan	25.5	*NO_3*	**5.75**	14.2	*PO_4*	**4.88**	**30.5**	[49]
Iraq	17.2	*NH_4*	**13.6**	10.2	*PO_4*	**3.50**	**12.9**	[50]
	0.850	*NO_3*						
Saudi Arabia	33.31	*NH_4*	**31.2**	6.56	*PO_4*	**2.25**	**6.50**	[51]
	23.48	*NO_3*						
Poland	0.0710	*NO_2/NO_3*	**32.5**	41.5	*Total*	**41.5**	**8.00**	[52]
	41.8	*NH_4*						

Table 1b
The possibility of using macronutrients recovered from pre-treated wastewater for fertilizer applications.

Macroelement	Nitrogen			Phosphorus			Potassium			Country	References
Yearly demand ***(kg/ha year)***	130			15.5			19.5				
m^3/ha/year	*kg/m^3*	*kg/ha/ year*	*demand %*	*kg/m^3*	*kg/ha/ year*	*demand %*	*kg/m^3*	*kg/ha/ year*	*demand %*		
$50.0\cdot10^{2}$	0.00500	25.0	**19.2**	0.00500	25.0	**161**	0.00580	29.0	**187**	**Israel**	[38]
	0.0202	101	**77.7**	0.0202	101	**652**	0.00560	27.8	**179**	**Israel**	[39]
	0.00660	32.9	**25.3**	0.00660	32.9	**212**	n.a.	n.a.	**n.a.**	**Jordan**	[40]
	0.0626	313	**241**	0.0626	313	**$20.2\cdot10^{2}$**	0.00210	10.4	**67.1**	**Italy**	[41]
	0.0277	139	**107**	0.0277	139	**894**	0.000100	0.470	**3.00**	**Italy**	[42]
	0.0199	99.5	**76.5**	0.0199	99.5	**642**	0.000100	0.280	**1.80**	**Italy**	[43]
	0.000700	3.35	**2.60**	0.000700	3.35	**21.6**	0.00860	42.9	**276**	**Italy**	[44]
	0.00660	33.1	**25.4**	0.00660	33.1	**213**	0.00400	20.0	**129**	**Greece**	[45]
	0.0420	210	**162**	0.0420	210	**$13.5\cdot10^{2}$**	0.00880	44.1	**285**	**Brasil**	[46]
	0.0505	253	**194**	0.0505	253	**$16.3\cdot10^{2}$**	0.000500	2.35	**15**	**Brasil**	[47]
	0.0476	238	**183**	0.0476	238	**$15.4\cdot10^{2}$**	0.00820	41.1	**265**	**Brasil**	[48]
	0.00580	28.8	**22.1**	0.00580	28.8	**186**	0.00490	24.4	**157**	**Pakistan**	[49]
	0.0136	67.8	**52.2**	0.0136	67.8	**437**	0.00350	17.5	**113**	**Iraq**	[50]
	0.0312	156	**120**	0.0312	156	**$10.1\cdot10^{2}$**	0.00230	11.3	**72.6**	**Saudi Arabia**	[51]
	0.0300	150	**115**	0.00500	25.0	**161**	0.0810	400	**$2580.6\cdot10^{2}$**	**Poland**	[52]

as a traditional fertilizer. Different regulations should be applied to reduce the nutrient abatement treatment when fertigation is expected. Policies should allow higher nutrient loads to the agriculture while saving energy costs and CO_2 emissions for the extended treatment. The experiences of countries that already introduced practical progress with reclaimed wastewater fertigation should be the basis for setting up EU legal standards. An example could be the case of Greece and Italy.

The use of secondary effluent for irrigation of agricultural fields reduces the amount of nutrients discharged into surface waters, thus reducing the environmental load. The wastewater reuse reduces the discharge load of nutrients into surface waters. On the other hand, the application and biogenic compounds to soil could increase the pollution of groundwaters. This should be monitored. However, this will be compensated by lower doses of N and P in the form of chemical fertilizers applied to cultivated crops. During non-irrigation period, retention reservoirs should be used or wastewater treatment should proceed to fulfill the requirements of pollutant loads in treated wastewater that is discharged to surface waters. The use of wastewater for plants nutrition and watering improves physical, chemical and soil fertility conditions [7]. Therefore, there will be a decrease in the risk of eutrophication, nutrients will not be squandered, while the expenditure on the purchase of fertilizers by farmers will be reduced [56].

Plants fertilized with reclaimed wastewater were characterized by high content of individual components and intensive vegetative growth (height and number of leaves) (Table 2).

Tomatoes under fertigation with treated wastewater produced more fruit and achieved significantly higher yields than plants watered with tap water [57]. The investigations, which were carried out on paddy fields, irrigated with reclaimed wastewater, did not show an increased risk to the environment or human health [58]. A two-year observation of microbiological quality and fruiting of bananas watered with reclaimed wastewater and water with chemical fertilizers did not show any significant differences [59]. Similar conclusions were drawn during irrigation of tomatoes and broccoli. No pathogens were isolated from any edible part of the plant, and the presence of pathogenic microorganisms in the soil was independent of the irrigation source [63]. Eight-year field studies of fertigated olive trees indicate good assimilability of fertilizer components from treated wastewater. Higher yields were also obtained in comparison with those attained under freshwater irrigation. The increasing soil salinity was observed, but it did not affect the yielding or increase of sodium or chlorine content in leaves. Fertilization may be a well-balanced process if there is sufficient rainfall to wash away excess salt from the soil [64]. Forty-year studies on the microflora of the soil irrigated with reclaimed wastewater did not show any significant differences compared to groundwater irrigation. Increased activity of soil enzymes due to the application of treated wastewater can accelerate the cycles of macroelements necessary for proper plant growth and thus improve plant yields [65]. Field studies on tomatoes have demonstrated that surface drip irrigation with treated wastewater does not provide soil and crop with pathogenic organisms. The results were not different from those for tap water irrigation [66]. Similarly, no significant changes in soil were observed and no pathogens were present on lettuce leaves watered with reclaimed wastewater using drip irrigation [47]. Twenty years of research on the effectiveness of fertigation with treated wastewater (alfalfa and maize crops) has shown no negative impact on soil quality. Moreover, a positive effect on β-glucosidase and alkaline phosphatase activity was observed, which indicates an improvement in soil physicochemical and biological properties [67]. During the eight years of irrigating with reclaimed wastewater of olive trees, there was no need for additional nutrient supply. What is more, the yield was higher than when irrigating with fresh water. However, increasing the salinity of the soil, in particular the absorption of sodium, may with further use of the effluent, cause the deterioration of soil properties [64]. The use of treated wastewater in the case of vines improved growth parameters, such as the content of chlorophyll in leaves and yield [68]. An interesting finding is the tendency to increase the weight and size of fruit of trees fertigated with reclaimed wastewater, which was observed in the case of nectarines [69]. Two-year field studies on sorghum cultivation showed that crops irrigated with reclaimed water resulted in a higher amount of dry matter and higher energy efficiency (over 10%) than crops watered with fresh water. The results show that the irrigation of crops for bioenergy purposes is justified [44]. Marinho et al. [70] used partially treated wastewater from anaerobic filters and intermittent sand filters in the fertigation of ornamental plants (roses) in greenhouses. It was found that the crop yield was 32% higher in roses fertigated with nitrified effluent from sand filters without deterioration of flowers quality. A high crop yield together with fertilizer reduction and water costs led to several benefits of such a solution. The authors of this study pointed out on long-term salinity accumulation problems. Vergine et al. [71] reported the results of field experiments on lettuce and fennel by using fertigation with reclaimed wastewater originating from 3 different streams from a given wastewater treatment plant. The three wastewater streams were characterized with different parameters (suspended solids, faecal indicators). Crop yields were higher when the level of fertilizer nutrients (in particular nitrogen) was higher in the treated wastewaters. This study confirmed that the source of nutrients for crops can be partially treated wastewater and this can reduce the application rates of chemical fertilizers. Contreras et al. [72] carried out studies on greenhouse pepper cultivation by using reclaimed wastewater. The studies showed that the main site of NPK accumulation was fruit. It was found that fertigation with recovered wastewater did not have a detrimental impact on vegetative growth, fruiting and fruit growth. The used concentration levels in fertigation water were as follows: $N–NO_3$ 0.3–6 mM, $N–NH_4^+$ 3.3–8.8 mM, P 0.37–0.63 mM, K^+ 0.6–8.2 mM, Ca^{2+} 4.8 mM, Mg^{2+} 4.2 mM, Na^+ 11.1 mM. Cl^- 8.9 mM.

Table 2

The effect of fertigation on specific plant types.

Agricultural species	Fertigation		Reference
	Effects	Challenges	
Tomato *(Lycopersicon esculentum)*	more leaves and higher plants than control (114.9% higher yields), higher content of macroelements NPK and Mg, Ca and Na in leaves, roots and fruits	ensuring a high level of wastewater treatment (sewage for food crops can cause diseases)	[57]
Rice	15% higher yield than the control	need to monitor the environment (water, soil, biodiversity of microorganisms)	[58]
Banana	the fruit ripened unevenly and faster, satisfactory fruit quality (similar to control)	dose selection of treated wastewater (may interfere with nutritional balance and fruit quality)	[59]
Olive *(Olea europaea)*	the leaf N, P and K concentration never fell to the deficiency value, reclaimed wastewater can provide 88% of the demand for N and 112% of the demand for K for olive trees	long-term impact of fertigation on soil condition (mainly salinity)	[39]
Lettuce	the contents of N, P and K in lettuce leaves were: 30–50 g·kg $^{-1}$, 4–7 g·kg $^{-1}$ and 50–80 g·kg $^{-1}$, respectively.	recommended crop evaluation with longer cultivation cycle	[60]
Grapevine	chlorophyll content between 30 and 33%, no negative impact on grapevine growth	risk of microbial and chemical contamination	[61]
Rosebushes	31.8% higher yield, but no significant difference between the use of treated wastewater and mineral fertilizers (economic profit)	soil salinity	[62]
Bean *(Vigna radiata)*	increased biomass and yield of plants irrigated with biologically purified sewage (as opposed to untreated sewage)	the need for wastewater treatment before use	[49]

The use of raw sewage contributes to nutrient imbalance and can provide the plant with toxic ions, which was observed during the cultivation of *Vigna radiata*. The results for the treated wastewater were satisfactory, with good yielding, which emphasizes the need to apply biological treatment before applying wastewater for irrigation [49]. In some cases treated wastewater needs to be diluted to meet the plant's nutritional requirements, as can be seen from *Hibiscus esculentus*, which required almost double dilution of wastewater to achieve the best growth parameters [73]. The dose of organic compounds that are necessary for the proper functioning of the soil, supplied during the application of recycled wastewater may be insufficient. It is recommended to be use additionally organic fertilizers during irrigation, the presence of which affects the proper soil structure and prevents heavy metals uptake and reduces the adverse effect of the presence of sodium in the soil [74].

It is necessary to adequately prepare wastewater for use in fertigation. Another issue is the concentration of fertilizer nutrients in fertigation with reclaimed water and plant requirements. It is probable that the correction of composition would be needed to match plant requirements.

The probability of negative effects related to the presence of undesirable compounds in reclaimed wastewater depends on many factors, like the type of component, its concentration, solubility, toxicity. Irrigation-related factors (irrigation frequency, climate type, soil and aquifer type) and social factors (social status, cultural level) also have a significant impact [75]. Irrigation with wastewater can have a negative influence on the ecosystem, in particular on soil and water quality. Continuous monitoring of both the composition of treated wastewater and the condition of the environment is very important. Wastewater can be also a source of pathogenic organisms (intestinal bacteria, viruses, parasites) and potentially toxic substances (salts and micropollutants). These contaminants can accumulate in soil, causing adverse effects on yield and on ecological aspects of soil. This is a challenge to elaborate a safe way of the agricultural re-use of treated wastewater. Health of the ecosystem can be assessed by monitoring bioindicators, organisms that represent biodiversity, i.e. arthropods [58]. The use of plant bioindicators gives information about the potential phytotoxicity of reclaimed wastewater for fertigation of plants. Wastewater from slaughterhouses (both raw and treated) showed phytotoxicity to cucumber and lettuce seeds, however treated wastewater showed lower phytotoxicity [76]. Industrial wastewater has a high phytotoxicity, mainly due to its heavy metal ions concentration, as was observed in the example of lettuce (*Lactuca sativa*) [77]. An important bioindicator for monitoring hormone toxicity in wastewater may be a mosquito (*Gambusia holbrooki*) [78].

The quality of the treated wastewater, including the content of microorganisms, suspensions or organic compounds, should be ensured; their presence may favor soil clogging and biofilm growth in the soil layers, aggravating capillary transport [79]. Furthermore, the presence of suspended solids could block the nozzles of irrigation devices [80].

3.1. Pathogenic organisms

The main disadvantages of using treated wastewater are the presence of pathogenic microorganisms and the impact of micropollutants. Pathogenic bacteria, viruses, common protozoa (*Giardia* and *Cryptosporidium*) and helminths may pose a direct threat to human health; hence, it is necessary to ensure that they do not pose sanitary-epidemiological danger if discharged to soil. Micropollutants are present in treated wastewater regardless of the treatment process. Different countries have specific guidelines, some do not monitor all types of pathogens, e.g. protozoa [81]. Faecal indicator bacteria are used to establish the microbiological characteristics of the water and it is suggested that viruses may be used for this purpose [82].

In 2017, the European Commission suggested that standards should be established for setting minimum quality requirements for water used for irrigation and replenishment of aquifers [83]. A report has been prepared, but it needs to be further specified, mainly in terms of the undesirable components to be monitored, the antibiotic resistance of the microbial consortia of microorganisms or the impact of wastewater treatment operations (disinfection or oxidation processes and their byproducts) on the composition of the treated wastewater [84]. For example, the reuse of treated wastewater in agriculture is regulated by law, microbial contamination (e.g. *Escherichia coli* <10 CFU 100 ml^{-1} in 80% of samples), which may become a standard for international guidelines. However, it has been found that the acceptable contamination of irrigation water should be below 1000 CFU ml^{-1} [85]. The presence of pathogenic microorganisms in the treated wastewater does not mean that they will pose a threat to human health after watering plants. The survival of these microbes is affected by many factors, including UV radiation and elevated temperatures in dry areas. Other factors, such as reduced humidity, the presence of consortia of soil microorganisms and the type of crop also play an important role and can determine the viability of pathogens [86]. The greatest concern is the presence of multidrug-resistant bacteria introduced into the soil along with the wastewater [87]. Few reports discuss the microbiological profile of fertigation using wastewater other than municipal wastewater. Beneduce et al. [63] used wastewater from the food industry for irrigation of tomatoes and broccoli, after the second stage of treatment. They proposed a closed-loop water cycle system to recycle water, studying the microbial content of water, soil, and plants. No contamination with pathogenic bacteria was observed in this case.

3.2. Micropollutants

Wastewater may contain various toxic compounds, including heavy metals, pharmaceuticals, hormones, detergents, industrial and agricultural compounds that have a negative impact on living organisms. Monitoring their concentrations in wastewater is difficult due to the need for advanced analytical techniques [75]. Often wastewater treatment plants do not control the concentrations of these compounds.

Microplastics from cosmetic products (such as toothpaste, face and body scrubs) or polymer fibers from washing carpets or synthetic clothes can get into municipal sewage. Mainly PET (polyethylene terephthalate) and PE (polyethylene) as well as smaller amounts of PS (polystyrene) and PP (polypropylene) are present in the wastewater [88]. Particles of microplastics are removed by sludge settling or skimming of solid particles in primary

Wastewater treatment [89]. The type and size of plastic impurities have a strong effect on plant growth. Microplastics can have a negative effect on the vegetative and reproductive growth of plants [90].

In alkaline soils, the presence of heavy metals in irrigation water is not a major problem in short-term application. Heavy metal ions bind to the soil and are not transported to the plant tissues. However, the risk of heavy metals entering the trophic chain must be taken into account during many years of use [91]. The reduction of the concentration of heavy metal ions can be achieved by diluting the treated wastewater with freshwater (e.g. in a ratio of 1:1) [92].

Studies on the accumulation of pharmaceuticals from treated wastewater in tomato fruit have shown that, there is a slow accumulation of these substances in plant tissues. The concentration of these compounds in the plant depended on the type of chemical agent, the time of application of the sewage, the type of sewage, or the season. This poses a potential threat to human health, but long-term studies are needed to verify this hypothesis [93].

Pharmaceuticals present in wastewater are most often analgesics and anti-inflammatory agents, antibiotics and psychiatric medicaments. It is also emphasized that the concentration of pharmaceuticals depends on the season: a higher adsorption of these components in the soil was observed in winter. Their presence in the soil irrigated with treated wastewater does not pose a high risk to terrestrial organisms (low-risk quotients); however, the concentration of pharmaceuticals should be constantly monitored for their movement into soil layers [94].

The presence of pharmaceuticals in wastewater used for irrigation can cause a number of consequences. Drugs can be a threat to the soil environment, accumulating in the soil for many years can affect microorganisms, soil worms, also causing the growth of antibiotic-resistant microorganisms [95]. Subsequently, the pharmaceuticals can be transported from the soil to the plants and thereby enter the food chain, being potentially hazardous to humans. There is still a possibility that these compounds may be released from the soil into groundwater or surface water, thus posing a risk to the biocenosis of aquatic organisms [95]. Detection of low concentrations of pharmaceuticals is difficult, costly and requires the use of special analytical techniques [96], including ultrasonic solvent extraction in combination with liquid chromatography [95].

Pretreatment for irrigation (tertiary wastewater treatment, i.e. using advanced oxidation processes (AOP) or membrane processes) allows for the removal of unwanted compounds (i.e. phenolic [97]), as well as fecal microorganisms from the wastewater. No significant restrictions have been set on the use of the secondary effluent as a source of fertigation [98].

3.3. Salinity

The hot climate is responsible for intensive evaporation and thus an increase in the concentrations of inorganic salts in wastewater [75]. Wastewater treatment plants usually do not include salinity removal methods such as reverse osmosis and nanofiltration, because they are relatively expensive. Unfortunately, long-term use of reclaimed wastewater as irrigation medium can promote salinization of the surface layer of the soil. Increased salt concentration in the root zone changes the osmotic pressure of the soil solution and disturbs the water uptake of plants [99] and may also be phytotoxic. The problem of soil salinity and sodicity particularly concerns closed systems, such as greenhouses [70, 100]. Higher salinity deteriorates physicochemical properties of soil through reduction of soil water holding capacity and its compaction. It also affects crop yield, causing physiological stress by imbalance of nutrients that results in disruption of photosynthesis, respiration, destruction of cellular organelles [101]. Special attention should be paid to hyper salinity and sodium toxicity risks, especially during long-term irrigation. The sodium content of the soil should be monitored during fertigation with reclaimed water [74]. Salts can be deposited in the soil through evapotranspiration, it is necessary to ensure a permanent removal of salt from the root zone to avoid adverse effects on plants [80]. In order for the plants to survive in conditions of increased salinity, they must be able to compensate the osmotic pressure inside. Plants can adapt to the new conditions through a number of mechanisms such as ion exclusion and adjustment of ionic strength in various parts of plant tissues. The energy used to overcome saline-related stress can have a negative impact on other vital functions, including plant growth. Growing plants that are resistant to high salt concentrations in the soil can be a solution to the problem of salinization.

Seven years of experience in irrigating grapefruit crops on two types of soils (sandy and clayey soil) and using reclaimed wastewater showed an increase in salinity in the upper soil layer at a depth of up to 1 m, but it decreased with each rainfall [102]. In the case of plants with low tolerance to salinity, drainage and washing of the outer soil layer is recommended. In addition, it is suggested to mix the water recovered from the effluent with fresh water in order to reduce salt concentrations [75]. Advanced techniques are used to desalinate treated wastewater, including membrane processes such as reverse osmosis. These processes are expensive, and moreover, when removing salt, nutrients are also removed, so the final result is clean water [9].

3.4. Nutrient surplus

Monitoring nitrate and nitrite levels in soils and plants is necessary when using reclaimed wastewater in agriculture. These are indicators of the environmental condition and directly contribute to the eutrophication of surface water. High concentrations of these compounds in the effluent may result in increased concentrations in plants, which is a threat to human health. They may be transformed into carcinogenic compounds (nitrites) or cause blood diseases [103]. The introduction of nitrates into plants results in their accumulation in plant tissues, in particular in leafy plants. This is the way in which most nitrates are incorporated into the human diet [104]. It is important to ensure a reasonable dosage of nutrients, preferably through more frequent and less intensive fertigation.

4. Irrigation with reclaimed water in practice

Nowadays, the use of treated wastewater as a source of water and plant nutrients is widespread in areas affected by water crisis. Israel is a leader in the use of wastewater for agricultural purposes. There, more than 95% of wastewater is treated, of which more than 80% is reused [66]. In Europe, slightly more than 2% of wastewater is used for irrigation [68]. Most wastewater is reused in Malta and Cyprus (over 50% on agricultural irrigation), in smaller amounts in Spain, Italy and Greece [105]. Due to the growing problem of hydrological drought in other countries, the use of treated wastewater as a fertigation medium may be an interesting solution. The literature presents many examples of the beneficial effects of long-term use of irrigation with treated wastewater, drawing attention to the risks associated with the introduction of some components of wastewater into the environment.

Sewage from the oil press was used to fertilize tomato and pea cultivation. The plant seeds were placed in pots and watered with pretreated and raw sewage within 20 days. It was found that fertilization with pre-treated sewage has a positive effect on sprout growth, as compared to raw sewage. Moreover, when watered with pre-treated sewage, plant growth parameters were similar to the control group. During the test, an increase in soil pH was observed, caused by ammonium production and organic acid mineralization. After 15 days of the process, the soil pH stabilized in most cases [97]. The treated wastewater from the olive mill was also used in maize cultivation. The analysis of soil and maize grain showed that the use of treated wastewater for fertigation positively affected the availability of NPK in the soil and the yield was similar to the yield obtained in the control group (mineral fertilizer) [106]. The literature also presents the influence of fertigation on the growth and yield of mung beans. The crop was watered with sewage, biologically treated wastewater and clean water. Fertilization of the first two caused a significant increase in NP content in plants. The use of raw wastewater negatively affected the total protein or chlorophyll content. However, fertigation with biologically treated wastewater increased plant yield [49]. This is another example confirming the idea of preliminary wastewater preparation before being used for fertigation purposes. The treated municipal wastewater was also used for pepper fertigation. Before fertilization, the wastewater was subjected to a three-stage treatment process. The group watered with treated sewage produced a fruit yield and quality similar to the control group, fertilized with traditional NPK fertilizer. No toxic elements were found both in the soil and in the fruit. Economic analysis showed that the use of treated sewage allows to save 37, 66 and 12% of elements in NPK fertilizer, respectively [107].

Worldwide, most wastewater is not treated [108]. Many countries use raw or partially treated wastewater, which poses a risk to human health and environment. Treated wastewater, which is one of the cheapest sources of recycled water, is currently used to irrigate 10% (representing 20 million ha) of the world's agricultural land [109]. The use of treated wastewater in agriculture should be implemented in a balanced manner, under the consideration of account various criteria. An evaluation model should be built that collect both environmental, social and economic aspects, striving to create a sustainable way of fertigation with reclaimed water. The economic aspects include costs of additional wastewater treatment and pumping to the irrigation area. Social issues are mainly related to market acceptance of products irrigated with reclaimed wastewater and ensuring protection of the farmers during irrigation. The last criterion covered environmental elements, including removal of unwanted components from wastewater (hazards and pathogens) [110].

Fertigation supports nutrients recovery [70]. However, the main environmental problems related to using reclaimed domestic wastewater include nitrates leaching, high levels of sodium that can cause soil sealing. Some of these environmental problems can be solved by the drip irrigation system that can reduce the risk of groundwater contamination, thus providing nutrients directly to the plant roots [70]. Drip irrigation also reduces evaporation and drainage of water, precisely places nutrients in the vicinity of plant roots [100]. Rahil et al. [100] supported fertigation and nitrogen management with mathematical modelling by using precise fertigation by underground droplet system. The following parameters can be modelled: flow of water, transport of nutrients, soil transformations of nutrients, nutrients and water uptake by crops. The mathematical models based on application rates of fertilizer nutrients and their losses by leaching have been elaborated.

Fertilization of plants relies on the knowledge of crop requirements, with special consideration for imbalances, uptake dynamics and accumulation in plant organs and tissues. Too high doses of ammonium-N cause impairment of other nutrients absorption (e.g. Ca) due to competition between NH_4^+ and Ca^{2+} cations [72]. The dose of fertilizer nutrients, for instance N, P, K, Ca, Mg in reclaimed water differs from requirements of crops. The concentration of N is too high, there is too low a level of P and K, whereas the level of salinity is too high [9]. In the study of Woltersdorf additionally 188 kg P and 85 kg K per hectare were supplied as chemical fertilizers.

Water recovery is associated with a number of barriers, including the fear of insufficient water quality, lack of awareness of the benefits associated with water recovery, lack of clear quality guidelines and risks associated with wastewater management for these purposes, high costs of water recovered in relation to the low price of drinking water and technical barriers [111]. The use of reclaimed wastewater also requires the employment of a number of sanitary procedures, overcoming social barriers (no public acceptance, barriers also for religious reasons [112]) or problems of transport costs over long distances (irrigation systems, pipe networks).

Wastewater is a source of water throughout the year, regardless of atmospheric conditions, with its amounts being virtually unchanged. Water recovery from waste water is an essential practice in the current era. Countries which for years practiced reckless generation of wastewater should change their attitude. However, in order to safely reclaim water, several standards must be met. Water quality standards, methods of water treatment, monitoring and control of water quality parameters should be assessed if wastewater is to be reclaimed [113]. Some countries have established guidelines for the use of treated wastewater, including Israel, Australia, Japan or Singapore [113]. There are no clear guidelines in Europe. Until now, the problem of wastewater recycling has only affected Mediterranean countries, but the drought which is spreading in northern Europe is enforcing such methods in these areas as well. Some countries use the standards recommended by the WHO, while others use California's Water Recycling Criteria. Both guidelines have large differences, which can easily be shown by the coliforms in the water for watering plants eaten raw. According to the WHO guidelines the amount should not exceed 1000 CFU/100 ml, while according to the second directive the limit is 2.2 CFU/100 ml [114]. In Italy this level is being reduced even to 10 CFU/100 ml [12]. Many guidelines do not address the presence of certain pathogens (e.g. protozoa) in reclaimed water, which can pose a significant risk to humans [81].

In Europe it is necessary to introduce regulations for the use of treated wastewater, its monitoring and control. Such guidance should include three components, in particular (1) limits on concentrations of toxic components and particular pathogens and methods of waste water treatment to achieve the desired results, (2) assessment of exposure to these components after release into the environment (soil, plants) and (3) assessment of human toxicity [113], (4) balanced control of the overall load of nutrients and recommendation to the farmers.In most places, the use of treated sewage for irrigation is incidental. This poses risks to human health, particularly in cases of vegetables fertigation. In order to avoid pathogen infections, the wastewater should be treated appropriately before being applied to the soil in particular for sanitary-epidemiological safety. Wastewater treatment plants mainly use nitrification/denitrification treatment or activated sludge treatment to reduce eutrophication of surface water. Such methods do not remove pathogenic microorganisms and, moreover, significantly reduce the presence of nutrients valuable to the soil [115]. Wastewater irrigation is also associated with the risk of infection with parasite eggs, including intestinal nematodes. The reason for this type of infection is also the lack of monitoring of such pathogens in sewage treatment plants. The risk is related not only to the agricultural worker himself, but first of all to consumers of the products. Research carried out in Aleppo showed that the wastewater used to irrigate vegetables contained 3340 eggs of *Ascaris*/L. The infection rate was 42% of the city's population, which excreted about 800,000 pathogen eggs per day [116].

There are alternative methods of treating wastewater from pathogens that could minimize the presence of parasites and pathogenic larvae (Fig. 3).

Additional wastewater treatment stages are costly, but this would solve environmental problems related with groundwater pollution. The lack of sustainable wastewater management results in the loss of valuable nutrients, which instead of being used for fertilization are discharged to surface waters. The increase in population and the standard of living of society lead to higher costs associated with drinking water supply, which additionally puts pressure to take new actions. Thus, the benefits of fertigation mean that the costs of wastewater treatment are concurrent with traditional water resources. Achieving a sustainable balance between the level of recovered waste water and safety issues is necessary to increase the efficiency of waste water reuse. Sewage treatment systems should be modernized and close to the "zero discharge" technology [117].

Quality parameters of reclaimed wastewater include the following classes: pathogens, salinity, toxic elements and nutrients (Table 3) [118]. These specific values are connected with the properties of the soil and the requirements of crops and human health.

In addition to the advantages of using reused water in agriculture, it is also necessary to take into account public acceptance, including farmers using reclaimed wastewater for irrigation and consumers of food produced in this way. The use of recycled water may not have the social acceptance. The feeling of discomfort is associated with the "yuck factor" which is a parameter expressing discomfort, disgust and other negative emotions associated with purchasing and eating plants from fertigation [125]. The degree of acceptance is also associated with the nomenclature, the most accurate description is "treated water", followed by "recycled water" and the most unfavorable acceptance was recorded for "treated wastewater" [126]. It is important to educate the public that treated wastewater can be beneficial despite its origin. Knowledge in this area and educational campaigns are necessary, starting with from an early age by organizing educational events in schools.

5. Stabilization of waste water during the storage phase

Among the various processes and systems of wastewater treatment, the storage of wastewater plays an important role, with no discharge to surface water or groundwater. The use of water storage allows the reuse of wastewater in the period when irrigation/fertigation is necessary. This would require to build the system of water retention reservoirs. This is included in the development strategy plan of many Member State of EU countries as the part of climate change adaptation actions. The storage tanks undergo numerous physical, chemical and biochemical changes. In the conducted studies, it was found that the quality of sewage/water is significantly improved when proper storage conditions are maintained [127]. In the seasons of the year when there is no need for irrigation, sewage retention (without a significant inflow) leads to biological processes in which the amount of pathogens and microorganisms is reduced. In the storage tanks, large oxygen production plays an important role, as well as solar radiation, which is attributed the greatest importance in pathogen reduction. The efficiency of the treatment is also improved by the stratification of the tank contents into the aerobic and anaerobic layer. The process of sedimentation improves physicochemical quality of wastewater by reducing the microorganisms associated with suspended solids [128].

The percentage removal of BOD, TSS and COD is determined by two parameters such as MRT (average residence time) and PFE (fresh wastewater fraction). It was found that the maximum BOD load of raw sewage can be 30–40 kg/ha/day. On an annual basis, the operation of the aeration chamber may reduce the content of COD, TSS and BOD up

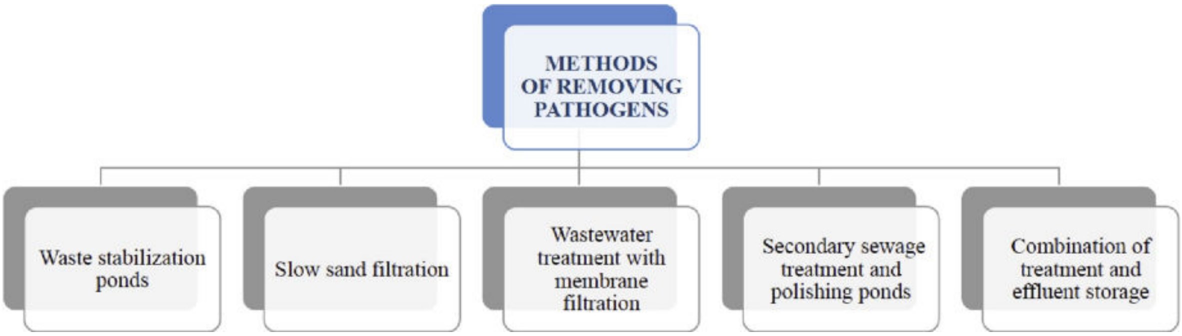

Fig. 3. Methods of treatment of pre-treated wastewater from pathogens.

Table 3
Criteria for irrigation with pre-treated water in different countries.

Guideline	Type	Unit	US EPA (2004)	Italy (2003)	Spain (2007)	Israel (2005)	Australian (2000)	Saudi Arabia (2009)	Hungary (2009)
			Reclaimed water for irrigation	Treated wastewater for reuse	Water quality for agriculture	Unrestricted irrigation	Effluent for irrigation	Criteria for irrigation - wastewater	Criteria for irrigation - wastewater
Nutrients	$N–NO_3$	*mg/L*	n.a.	5.50	n.a.	n.a.	n.a.	n.a.	n.a.
	Total N	*mg/L*	10.0	15.0	10.0	25.0	50.0	n.a.	n.a.
	P	*mg/L*	5.00	2.00	12.0	n.a.	10.0	n.a.	n.a.
Micronutrients	Co	*mg/L*	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	2.00
	Cu	*mg/L*	0.200	1.00	0.200	0.200	0.200	0.400	0.100
	Fe	*mg/L*	5.00	2.00	10.0	2.00	0.200	0.100	1.00
	Mn	*mg/L*	0.200	0.200	0.200	0.200	0.200	0.0100	0.0100
	Mo	*mg/L*	0.0100	n.a.	0.0100	0.0100	0.0100	0.0200	1.00
	Se	*mg/L*	0.0200	0.0100	0.0200	0.0200	0.0200	4.00	5.00
	Zn	*mg/L*	2.00	0.500	2.00	2.00	2.00	n.a.	n.a.
Salinity	Na	*mg/L*	n.a.	n.a.	n.a.	150	n.a.	n.a.	n.a.
	Suspended solids	*mg/L*	n.a.	10.0	20.0	n.a.	n.a.	n.a.	n.a.
	pH	-	6.00	6.00–9.50	n.a.	6.50–8.50	5.00–8.50	6.00–8.50	6.50–8.50
Pathogenicity	*Escherichia coli*	*CFU/* 100 ml	n.a.	100	100	n.a.	n.a.	n.a.	n.a.
	Faecal coliforms	*CFU/* 100 ml	n.a.	n.a.	n.a.	10.0	n.a.	n.a.	n.a.
Heavy metals	As	*mg/L*	0.100	0.0200	0.100	0.100	0.100	0.500	0.200
	Cd	*mg/L*	0.0100	0.00500	0.0100	0.0100	0.0100	0.0100	0.0200
	Pb	*mg/L*	5.00	0.100	n.a.	0.100	2.00	0.200	5.00
References			[119]	[120]	[121]	[122]	[123]	[124]	[124]

to 80% and coliforms up to 90%. The quality of wastewater ready for irrigation/fertigation process is the best in the initial period of the season, due to the filling with wastewater, unfortunately, with the inflow of new wastewater it significantly deteriorates. The solution to this problem is, among others, to increase the number of tanks, which are characterized by different stages of treatment, or multi-season storage of wastewater [129]. It was found that much greater effects of pathogen removal are obtained during the process conducted periodically, without a continuous inflow of raw sewage [130]. Research shows that one of the most important aspects of wastewater storage is the design of the tank and its management. When designing a tank, attention should be paid not only to such parameters as the volume, type of tank or climate-related criteria, but also to the ratio of the amount of waste water entering to the tank containing waste water. One of the difficulties in using this type of tanks is the large area required for their proper operation [131].

The wastewater storage stage can be a very important part of wastewater treatment for re-use. The introduction of wastewater into the cleaning line element, which is a stabilizing tank, can provide a solution to the problem of pathogens and undesirable microorganisms. However, the whole process needs to be optimized and constantly controlled to maintain constant parameters during the irrigation season [132].

6. Practical implications of this study

The present section underlines the challenges of the current review, future work and provides recommendations.

Trends in resource recovery of wastewater should be discussed in terms of economic and environmental sustainability. The process of recovery of nutrients, water and energy from wastewater should be furtherly studied and should include life cycle assessment and life cycle cost analysis when considering the effect of process conditions. The impact of temperature, flow rate, emission, system centralization/decentralization is an important aspect for future studies. Further research is required for thermal energy recovery system and optimization of wastewater systems which make it possible to recover resource in diversified ways [133].

Impact of environmental conditions on analysis of load of nutrients in recovered wastewater requires more research. The discharge of macronutrients (NPK) and microconstituents to the environment in terms of their further fate is important. The pathways of transformation of those components in soil require more attention. For instance, it was found that for N the mechanism was mainly biodegradation, for P adsorption and for micropollutants the combination of biodegradation and photolysis [134].

Public policies designated for water security and sustainability and using reclaimed water in agriculture have high impact on practical application of this solution. The importance of public policies in terms of using reclaimed wastewater in the context of climate change is a valid issue. The need for new water management rules and European regulations for circular economy to support environmentally friendly infrastructure should be implemented [135].

Sustainable management of non-conventional water resources for soil remediation requires detailed planning. Soil and water are presented as the most important resources in food production. For this reason, deficiency of fresh water is an important challenge for food security. Useful, particularly in degraded areas can become non-conventional water resources, such as wastewater or greywater. Important is to monitor changes in chemical, biological and physical parameters. Significant for future development of this strategy is to successfully introduce legislation to encourage both farmers and wastewater treatment plants to cultivate crops which are resistant to pollutants, e.g. carrots, lettuce, cucumbers, tomatoes. Reuse of wastewater should become an integral component of strategic national development plans. Of course, safety of such solution should be a priority. This can be achieved through the properly planned financing, environmental management and resource planning [136].

Nutrients (N and P) recovery from wastewater in the view of circular economy is a key issue in depletion of non-renewable resources. Nutrients recovery technologies are not fully optimized for the sake of commercialization and efficiency. Application of different technologies can be possible to recovery nutrients from wastewaters: biological nutrient recovery, crystallization of membrane techniques [137].

7. Conclusions

The important aspects of wastewater reuse include growing global water scarcity, insufficient treatment and wastewater disposal plus increasing costs of fertilizers. Wastewater is a source of plant nutrients and organic matter, but it may be contaminated with chemicals and pathogens, which can lead to secondary environmental pollution. Exploiting the potential of fertigation for reclamation of partially treated wastewater is a challenge and requires modifications of existing wastewater treatment technologies and agricultural practices. Careful planning and management are important. It is necessary to change the system of managing water and nutrients from wastewater. Treated wastewater contains valuable nutrients for plants and its use for crop irrigation is part of the circular economy concept. Further research and socio-economic work is needed before taking full advantage of existing opportunities. The recovery of organoleptic properties of reclaimed water is also important in terms of possible odour emissions.

For this reason, preliminary installations in real systems need to be set up to elaborate the rules of fertigation with reclaimed water for the soil and climatic conditions of a moderate climate. Only practical testing on the experimental plots adjacent to wastewater treatment plants could confirm usefulness of this method for watering and nutrition of plants in moderate climate countries. Monitoring of environmental consequences of fertigation with reclaimed water is essential in practice, in particular monitoring of the potential increase of biogenic compounds, toxic elements and micropollutants in soil and groundwater environment. Also, the possible change of soil characteristics in terms of biological, chemical and physical properties should be monitored. Very important aspect is the possible bioaccumulation of pollutants by crops and testing for the potential phytotoxicity in plants.

Considering the scale of agricultural production and the related scale of fertilizer use, it is currently not possible to completely replace chemical fertilizers with plant nutrition from partially treated wastewater. However, the gradual introduction of such a solution will be an important step-forward towards practical implementation of circular economy and sustainable crops production. Currently, there are still organizational and technological limitations and further progress in this area is required. It is also important to encourage farmers and sewage treatment plants through co-financing of such adaptations. This is particularly important for popularization of this strategy.

CRediT authorship contribution statement

K. Chojnacka: Supervision, Conceptualization, Writing - original draft, Writing - review & editing. **A. Witek-Krowiak:** Supervision, Conceptualization, Writing - original draft, Writing - review & editing. **K. Moustakas:** Supervision, Writing - original draft, Writing - review & editing. **D. Skrzypczak:** Writing - original draft, Formal analysis. **K. Mikula:** Writing - original draft, Formal analysis. **M. Loizidou:** Supervision, Writing - review & editing.

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