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Wastewater and sludge reuse: selected case studies across the globe

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ABSTRACT

The recovery and reuse of resources are key points towards a sustainable development. Due to an ever-growing water demand, wastewater is gaining momentum as a reliable alternative water source. In the same context, sewage sludge is now recognized as a valuable resource, and not as a waste, and its valorization for nutrients and/or recovery of energy is making progress. This review focuses on the descriptive analysis of the status of wastewater and sewage sludge reuse in selected countries worldwide (Greece, Israel, Perú, Philippines and Spain), representing four continents. Generated wastewater and sludge, treatment strategies, wastewater reuse standards applied in each of the studied countries, economic aspects, public acceptance and constraints issues are presented, along with a case study of nanotechnology application for water improvement and wastewater reuse in Israel. A potential for further increase of the reuse of both sewage and sludge has been identified for all countries. Similarly, sludge reuse must be significantly enhanced for energy production and agricultural applications. In the Philippines, reuse is successfully practiced especially with domestic and food producing and distillery-based wastewater. In Spain, there is still great potential to increase the reuse areas for reclaimed wastewater application, while an important part of the sludge is already used in agriculture. In Israel, nanotechnology treatment approaches have been proved important in arid regions with minimal amounts of precipitation. The main goal of this review manuscript is to provide updated information regarding wastewater and sludge reuse for the worldwide benefits.

Keywords: Wastewater; Sludge; Reuse; Irrigation; Agriculture; Ultrafiltration; Reverse osmosis; Nanotechnology

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1. Introduction

Global freshwater resources are under increasing stress. Significant mismatches between the demand for, and availability of water resources across temporal and geographical scales increase every year. With this scenario, water shortage fosters the development of alternative water resources that could better cope with the impact of climate change and population growth on freshwaters [1–4]. Treated wastewater (TWW) can serve as a solution for water demand especially in arid and semi-arid zones, where it is primarily used for irrigation [5,6]. However, issues as the acceptance of reclaimed water segregation as a separate water stream, allows its safe reuse. Multiple issues to be also considered in reuse are human health, effects on soil, sustainability, risks associated with the environmental and health impact and water availability of each country. Despite of the above-mentioned issues, TWW is expected to be one of the new water resources that will be used soon on regular basis, primarily in the growing mega-cities, which face problems linked to the high expenses associated with wastewater and freshwater treatment and conveyance. Interestingly, wastewater reuse will be even more profitable when combined with the runoff collection, greywater and other low-quality waters resources. The main problem associated with wastewater reuse is the quality of the water and the targeted reuse options: salinity, macro and micropollutants, emerging contaminants, level of treatment and expected use. These issues stem from the diverse quality of the raw wastewater and the treatment options and reuse.

Managing water scarcity is a global challenge that affects environmental, social, economic, health and political aspects of human life, including food production. Our ability to respond to the increasing risks of water scarcity could be enhanced by wider reuse of TWW for agricultural, industrial, urban and other uses. Water stress is not only an issue for regions with high population density and low rainfall, however, also for areas with intense agricultural, industrial, and tourism activities. Global climate changes have been partly responsible for the increased frequency and intensity of droughts events over the last decades, while predictive models' projections are threatening the future [7,8].

Effluent reclamation and reuse provide the means for efficient utilization of water and the conservation of the quality of existing fresh water sources [9]. However, no advantage is currently taken of the potential of treated wastewater reuse, since most wastewater is nowadays discharged into water bodies, and over 80% is estimated to be discharged without previous treatment. Wastewater treatment is estimated at 70%, 38%, 28% and 8%, for high, upper middle, lower middle, and low income countries, respectively. The reuse of municipal wastewater is a common pattern in the Middle East, North Africa, Australia and the Mediterranean countries, as well as in China, Mexico and the USA [10]. While a relatively high percentage (71%) of the municipal and industrial wastewater operated in Europe undergoes treatment, just 51% is treated in the Middle East and North Africa, and only 20% in the Latin American countries [11].

Almost half of the European river basins will most probably be affected by water stress and scarcity by 2030 [8]. Although more than 40,000 Mm^3 of wastewater are annually treated in EU, only 964 Mm^3 are reused [8]. According to estimated predictions (AQUAREC project, 2006), a treated wastewater reuse volume of 3.2 Mm^3/y in Europe is predicted by 2025. However, according to EC authorities, more regulatory and financial motivations could support water reuse of more than 6,000 Mm^3/y by 2025 [8]. At the European level, new regulations on minimum requirements for water reuse for agricultural irrigation were published recently and will be fully employed in coming 3 y. The new regulations have been set in the context of the new Circular Economy Action Plan adopted in 2020, which include the application of the new Reuse Regulations amongst Europe's priorities for the circular economy [12].

The hypothesis is that reuse of treated wastewater can relief water stress worldwide. The main objective of this review is to underline the benefits of wastewater and sludge reuse in integrated water resources management systems and the role of reuse in the economic cyclic management systems. Selected countries representing different continents were studied, to provide updated information on these issues, which reflect worldwide trends. Data on produced wastewater and sludge, treatment strategies, wastewater reuse standards, economic aspects, public acceptance and constraints issues for Perú, Philippines, Spain, Greece, and Israel are provided. A case study of nanotechnology application for water improvement and further wastewater reuse is also summarized for Israel. The updated information regarding wastewater and sludge cycles will further support the development of appropriate technologies and effective policies for the productive and safe reuse of these resources. These will probably be contributing phases for solving water scarcity issues, support climate changes adaptation, help to maintain good health of environment, improve decision making, and promote Circular Economy.

2. Wastewater and sludge reuse in Perú

Perú generates approximately 2.2 Mm^3/d of sewage of which only 40% is treated [13]. Wastewater treatment in Perú is predominantly handled by Sanitation Services Providers (SSP) operating in 253 sites. None of these locations are served by centralized or decentralized wastewater treatment plants. Out of a total of 143 recorded functional wastewater treatment plants (WWTP), only several are considered successful projects [14]. It is mainly due to the absence of a culture of environmental protection and the reluctance of SSP to evaluate the environmental and socio-economic potential of the treated wastewater. In the rural areas, and in regions where the population is less than 2,000 inhabitants, there are no treatment plants. In fact, only a 5% of the rural villages have a kind of wastewater treatment facility. In these areas the treatment of wastewater is either administered directly by the municipalities, operated by the adjacent small towns' authorities, or simply not managed at all.

The most widely implemented (approximately 75% of the facilities) wastewater treatment technology in Perú are lagoons systems: anaerobic, facultative or aerated [13]. The operation and management strategies of such lagoons is poor. As per a study conducted in 2015 by the Peruvian SUNASS (National Superintendence of Sanitation Services) company [13], 85% of the evaluated WWTPs did not have a treatment to allow the removal of 3.6 log units of total coliforms to meet the law of maximum permissible limit (MPL). Organic and hydraulic overload has been recorded in more than 50% of the plants in Perú, and the existing design of the treatment plants is still one of the major limiting factors to the achievement of higher standards of treated wastewater [15].

In terms of sludge characteristics, often no maintenance or monitoring (i.e., sludge bathymetry or composition) is applied by the plant team. In some cases, malfunctioning of the plant is due to the lack of proper technical equipment to remove the sludge from lagoons (dredgers and pumps). The overall mismanagement of sludge is the cause of delayed actions by the Peruvian municipalities that have to work under difficult conditions like plant-overload. Out of 42 WWTPs investigated in the above quoted study by the SUNASS [15], only one was able to desludge their lagoons without having to drain them. The rest of WWTPs used the lagoon as a drying bed to further remove water from the sludge. This significantly affects the efficiency of WWTPs, because most of them do not have enough reserve capacity to withstand the lack of operation of the dried lagoon.

In recent years, the acute water shortage in the coastal area of Perú forced the municipalities to implement wastewater treatment plants with activated sludge technologies. The large quantity of sludge produced by the plants is currently creating a new concern. Despite activated sludge systems being considered as a good option to meet current sanitation needs of the country, sludge drying bed technology is still rare in Perú [16]. This is indeed available only for big cities. Many municipalities are not able to afford the mandatory disposal of dehydrated sludge in landfills which is, in general, costly. The main sludge stabilization technologies up to now have been co-composting and anaerobic digestion [15].

2.1. Laws and directives

2.1.1. Laws and directives controlling wastewater and sludge

Perú does not have a comprehensive legislation for wastewater disposal or reuse. Also, there are no authorized landfills for the final disposal of sludge from WWTPs. Moreover, the lack of environmental quality standards and regulations for sludge management, hinder the process of using sludge in agricultural applications.

2.1.2. Laws controlling water resources management

Main rules for water resources management in Perú are the regulations No. 17752 (1969) and No. 28611 (2005) which cover marine waters, terrestrial and atmospheric conditions of the national territory, as well as the protection of the environment (D.L. 17742, 1969 and 28611, 2005) [17,18]. The Ministry of Health, through the Directorate General for Environmental Health (DIGESA) is responsible for ensuring the preservation of the quality of the water resources with the law DS No. 023-2005-SA (2006). The DIGESA has recently established MPL to strengthen the sanitation-related technical standards. On this basis, the DIGESA evaluates and grants the authorization for the reuse or discharge of wastewater in water bodies (Table 1). Likewise, the Ministry of Housing, Construction and Sanitation is responsible for monitoring and sanctioning the non-compliance of MPLs in municipal or industrial wastewater treatment facilities. It should be noted that the law does not require Sanitation Safety Planning (SSP) to monitor the parameters and also the governing body does not have control of the regulation and capacity of sanctioning the lack of fulfilment of the MPLs.

2.2. Use of wastewater and sludge in agriculture

In 2007, approximately 66% of the total wastewater treated by WWTPs was reused [13], of which 43% for agricultural applications. Interestingly, approximately 8% of the effluents from the WWTPs in Lima were used to irrigate recreational areas [19]. It has been estimated that approximately 13,200 ha of agricultural land and green spaces are irrigated with treated wastewater in Perú. Interestingly, 95% of this land is located on the coast [13].

Stabilization ponds in different combinations with retention time of at least 10 d, has been the preferred treatment method for reuse applications. Ten days is sufficient in most of the cases to comply with the microbiological requirements of restricted irrigation to high stem, forage, and forest crops [20–22]. These crop categories are also the most cultivated in Peruvian agriculture and irrigated with reclaimed water (Table 2). Other technologies such as the activated sludge are usually kept at shorter retention times. This is worrying because such effluents, if used for irrigation of urban areas, might be a risk for public health. It is true that some of these WWTPs include additional disinfection by chlorination, however, such process can hardly inactivate parasites.

Irrigation is usually performed by gravity methods such as flood and furrows [13,20]. Gravity methods are usually the key factor of risk of food contamination, via direct contact of the water with the crops [22]. Recently, more sophisticated irrigation methods have been applied in some areas of Perú: spraying, micro-spraying and dripping are safer irrigation methods because they impede water contact with the crops and infiltration almost does not-exist [13].

2.3. Reuse of sludge in Perú

Even though there is no specific documentation regarding sludge reuse, the foreseen increasing amount

Table 1
MPLs for treated effluent to reach water bodies in Perú, as per DS No. 003-2010-MINAM

Parameter	Value
Oils and fats, mg/L	20
Thermotolerant coliforms, NMP/100 mL	10
Five-day biochemical oxygen demand (BOD_5), mg/L	100
Chemical oxygen demand (COD), mg/L	200
pH	6.5–8.5
Total suspended solids (TSS), mg/L	150
Temperature, °C	<35

of wastewater treated with an activated sludge technology is pushing practitioners and the scientific community to look for sustainable disposal and reuse of sludge [13,23]. Final disposal as well as the rising economic and environmental costs of this practice is of high concern. When elevated amounts of toxic components such as heavy metals are present, sludge is classified as a hazardous waste and is used only for activities or disposed in landfills (Decreto Supremo N.° 057-04-PCM) [24]. The applicability of sludge as a soil conditioner is allowed; however, at present Perú does not have technical standards determining their applicability. Atencio et al. [25] performed some studies in Perú to assess the toxicity of heavy metals in sludge produced in Puente Piedra WWTP in Lima. The sludge generated by the plant met the sanitary and environmental requirements, thus allowing their use in agriculture. The crops amended with dried sludge did show a better growth and yield compared to the control crop; however, the heavy metals concentrations in soils exceeded the maximum permissible concentration as per USEPA and Consortium for Energy Efficiency (CEE) standards (625/10-84-003 and 86/278/CEE) [25,26].

3. Wastewater and sludge reuse in the Philippines

3.1. Wastewater and sludge production

In the Philippines, only 10% of wastewater is treated and only 5% of the population is connected to a sewer network [27,28]. In the urban areas, the Metropolitan Waterworks and Sewerage System (MWSS) is mandatory for water supply, sewerage, and sanitation; for example, in Metro Manila area and some adjacent provinces.

Table 2
Main crops irrigated with treated wastewater in Perú [13]

Type of crop	Coastal area	Mountain	Forest	Total (ha)	Percentage (%)
Gramalote	3,000			3,000	30
Alfalfa	400	22		422	4
Elephant grass	1,000			1,000	10
Maize	770	91		861	9
Cotton	380			380	4
Cochineal	950	26		976	10
Fruit		472		472	5
Vetch	120	26		146	1
Olive	10			10	0
Rice			2,700	2,700	27
Total	6,630	637	2,700	9,967	100

Manila Water Company, Inc. (MWCI) is one of the two concessionaires of MWSS. The company supplies the eastern portion of Metro Manila as well as the province of Rizal with water supply and wastewater services. The area includes over 6 million people, of which 1.6 million belong to low-income communities. MWCI has 37 sewage treatment plants with a total capacity of 140,600 m^3/d which is equivalent to 12% sewerage coverage [29]. The collected sludge from the septic tanks in the East Zone is brought to the MWCI's North and South septage treatment plants, which has a combined treatment capacity of 1,400 m^3/d.

The treatment processes include: (i) primary treatment which involves screening, grit and scum removal, and; (ii) secondary treatment with activated sludge process. This is followed by a coagulant-assisted mechanical dewatering in screw presses for the sludge, including adding polymers and mechanical compaction for stabilization and subsequent reduction of volume.

On the west zone of Metro Manila, the concessionaire is the Maynilad Water Services Inc. (MWSI). The company has 14 sewage treatment plants with a total capacity of 516,900 m^3/d and two septage treatment plants with a combined total capacity of 700 m^3/d. The 16 sewage treatment plants (STPs) and septage treatment plants (SpTPs) are a mix of several technologies such as conventional activated sludge (CAS), sequencing batch reactor (SBR), moving bed biofilm reactor (MBBR), STM-aerator, and the membrane bioreactor (MBR). Table 3 indicates the annual wastewater treated and the accepted treated sludge/biosolids for the concessionaries of MWSS.

Aside from the East Zone, MWCI also provides water supply and sewage treatment to areas such as Clark, Boracay Island and Pampanga. In 2014, wastewater treated in these areas had a total volume close to 9,640,000 m^3.

3.2. Practices of wastewater and sludge reuse in agriculture

The filtrate (liquid component) in the septage is treated further in a conventional sewage treatment facility. The treated effluent is disposed to nearby water bodies and the residual volume is recycled for landscaping, cleaning of equipment and containers in SpTPs. The dewatered sludge (biosolids) is then brought to lahar-affected areas in Central Luzon for composting and inoculation in preparation for use as organic soil amendment in the corn and sugarcane plantations.

For Manila Water Company Inc. (MWCI), the biosolids are further processed by service providers to yield higher

Table 3
Annual wastewater treated and treated sludge/biosolids for the concessionaries of MWSS

Concessionaire	Wastewater and sludge	2012	2013	2014
Manila Water (East)	Wastewater treated (m^3)	28,063,770	28,055,477	28,714,077
	Biosolids (tons)	16,093.97	13,485.31	19,505.44
Maynilad (West)	Wastewater treated (m^3)	41,540,000,000	40,540,000,000	44,620,000,000
	Biosolids (tons)	–	15,910.64	11,023.26

value soil conditioners and these are given or sold to corn, sugarcane, and mango producers in lahar-affected areas in Tarlac and Pampanga. Throughout the biosolids management program, MWCI assisted in the rehabilitation of farmlands affected by the eruption of Mount Pinatubo in 1991, providing both an economical and environmentally sustainable method of biosolids disposal and reuse, and created employment and agricultural benefits to an area severely struck by a disaster.

In the case of Maynilad Water Services Inc. (MWSI), biosolids in combination with chemical fertilizers were used to enhance soil nutrients fertilization and improve moisture retention capacity to obtain higher sugarcane yields. Biosolids can be mixed with farm residues such as bagasse, mudpress, and mill ash, among others, to be converted into organic fertilizer through composting and vermicomposting. The practice resulted in development of cheap, environment-friendly fertilizer for the use of sugarcane farming in the lahar-ravaged areas of Pampanga and Tarlac, two rice producing provinces in the main island of Luzon, in Philippines.

Distillery effluents are also reused as substitute or supplementary for chemical fertilizers in sugarcane fields. It was observed that cane and sugarcane yield of the first season crop (plant cane) were remarkably increased by 64%–71% and 37%–69% over the control by applying distillery effluent. Effluent application significantly increased soil potassium but not soil pH, organic matter content and available phosphorus. The effluent also increased the ash and/or potassium content of the juice [30].

3.3. Critical values of soil heavy metals for the control of wastewater and sludge application

In a study by De Sales [31], it was observed that the septage in Metro Manila does not contain large amounts of heavy metals that can cause soil and groundwater contamination. When applied in excessive amounts, septage containing ammonia can be oxidized to Nitrate-N in soil and can lead to groundwater contamination. This can be prevented by introducing vegetation, since these can assimilate Nitrate-N in the ground.

3.4. Quality of agricultural products produced with wastewater and sludge reuse

From the study of De Sales [31], irrigation and amount of sludge applied are significant factors on the growth of talahib (*Saccharum spontaneum*) grass. The ideal amount of septage was found to be 80 L/m^2. The maximum sludge application was 130 tons/ha. Septage begins to manifest its effect on the growth-height of the talahib after four weeks while peachy (*Brassica rapa*) reacted after 10 d. There was an observed increase in the length of the plant leaves.

Maynilad (MWSI) has drawn up a memorandum of agreement (MOA) for the sugar regulatory administration, regarding the use of biosolids in combination with chemical fertilizers for enhancing soil nutrients and improving the moisture retention capacity, for the obtention of higher sugarcane yields. Septage and biosolids were applied in the experimental sugarcane farms of the Luzon Agricultural Research and Extension Center Paguiman, Florida Blanca, Pampanga, north of Manila. Parallel to these activities, an information and education campaign was conducted through the Pampanga Mill District Farmers Cooperatives for educating the farmers regarding the effective and proper use of septage and biosolids. The practice resulted in the development of cheap, environment-friendly fertilizer for the use by sugarcane farmers in the lahar-ravaged areas of Pampanga and Tarlac. Farmers no longer must apply expensive chemical fertilizers, as Maynilad provides and transports the septage and biosolids for free.

4. Wastewater and sludge reuse in Spain

Spain has a population of nearly 46 million inhabitants, served by around 2,000 wastewater treatment plants treating an amount of 4,097 Mm^3/y and the specific water consumption is around 102 m^3 per inhabitant per year. It is estimated that 80% of the population has access to wastewater treatment facilities. There are a few towns still attending wastewater treatment plants, but the majority of untreated wastewater come from small villages (<2,000 p.e.).

The main amounts of the large wastewater treatment plants (over 20,000 p.e.) are using the activated sludge technologies. The sludge is quite always stabilised using aerobic or anaerobic digesters. When the facility is large enough, anaerobic digestion is mainly employed, and methane gas is generated. This gas is usually reclaimed for energy generation. Digested sludge is dehydrated by the common techniques such as centrifuges, filtering devices (press belt) or drying beds for small facilities. Coagulation–flocculation and filtration is the most common reclamation train, while there are more complex (even including membrane technology such as reverse osmosis) or simpler ones (natural systems). Disinfection is performed quite always by UV light or chlorination, with a few facilities using other technologies.

4.1. Reclaimed water and reuse

It is estimated that the reuse capacity of Spain is around 1,200 Mm^3/y, but the real reuse figure is around 400 Mm^3/y. Nevertheless, reuse depends on the climatic conditions of each specific year. There are regions (e.g., Murcia) where quite all treated/reclaimed wastewater is used, mainly for agricultural purposes, while in other regions only less amounts of reclaimed water are used. The regions where reuse is practiced coincide mainly with the Mediterranean climate area of Spain and a few with other in the Atlantic Basins (mainly in Madrid and some scattered localities). The main uses of reclaimed water are in agriculture, golf courses irrigation, and industrial/cooling systems. Other uses are anecdotic like Managed Aquifer Recharge, water bodies' recovery and flow increase, vehicles and ships cleaning, and other urban uses.

There is a decree in reuse (R.D. 1620/2007) heavily contested, and the brand-new EU regulation has just entered into force (June 2020) and will be fully applied in 2023. The old Spanish decree suffered from a great number of failures and technical inconsistencies.

4.2. Sludge use

In Spain, there is a register (National Register of Sludge) of the amount of sludge generated during wastewater treatment. The amount produced is around 1.2 million tons/y as dry matter [data from 2015, 32]. The sludge generated in the Spanish wastewater treatment plants is considered as a waste and due to regulation 10/1998 that waste has to be applied in agriculture, as well as the Royal Decree 1310/1990 is indicating [33,34]. The priority is to use sludge in soils and afterwards other forms of valorisation must be considered. The last option to be employed is the elimination on landfills.

The most usual practice is the application of sludge to agricultural lands, considering that there are limits in respect to the heavy metal contents of sludge and soils. Those limits are fixed by the law depending mainly on the soil pH. Sludge must have been treated biologically, chemically or by using thermal procedures. Long term storage or other processes can also be used to reduce in a significant way its fermentation power and the sanitary problems derived from their use in soils. It is compulsory to consider the nutrients needs of the plants to fix the application doses. This is done in a way that water and soil quality should not be affected.

Sludge can be applied to agricultural soils following the indicated in the mentioned RD 1310/1990 (October, 29th) regulating the use of sludge in the agricultural sector, incinerated or co-incinerated in cement factories as indicated in the RD 815/2013 (October 18th) approving the rule of industrial emissions and developing law 16/2002 (1st July) preventing and controlling in an adequate way the pollution, or disposed in sanitary landfills always complying the conditions established in the RD 1481/2001 (December 27th) regulating the elimination of waste in sanitary landfills. The information sent to the National Register of Sludge must include the information which includes all wastewater treatment plants. Sludge treatment facilities and agricultural application managers should facilitate according to the Order AAA/1072/2013 (June 7th) on use of sludge in the agricultural sector. The agricultural practices for application of sludge, if allowed, are the usual for applying manure, that is, the material is applied over the land and subsequently is mixed with the soil. A study published in the year 2009 by the government (Ministry of Environment and Rural and Marine Environment, MARM) describe the required quality of the sludge [35].

5. Wastewater and sludge reuse in Greece

5.1. Wastewater reuse

There are more than 350 wastewater treatment plants in Greece, most of which serve settlements and cities with more than 15,000 inhabitants each. More than 91% of the Greek population is connected to WWTPs [36]. Communities with 2,000–15,000 residents, have a limited service. A remarkable pressure on water resources has been predicted for Greece by 2050, compared to 2010 [37]. The reuse of reclaimed wastewater has become a component of long-term water resources management, in numerous European Union countries with water scarcity problems, including Greece. However, overall a small proportion of reclaimed wastewater is reused [38]. The use of treated wastewater in Greece is regulated and authorized for agricultural irrigation, landscape irrigation/golf courses, aquifer recharge, environment control, industrial recycling and urban use [38–41].

Wastewater is subjected to primary treatment at approximately 1%, while 83% is subjected to secondary and 16% to advanced treatment. Eighty per cent of the WWTPs are based on activated sludge systems. Treated wastewater is reused only to a limited scale, and most of it is disposed to surface water bodies. Eighty-three percent (83%) of water consumption in Greece is dedicated to irrigation, while only 1% of the produced wastewater is reused for irrigation [10,42]. According to estimations, approximately 18,000 ha are being irrigated with different agricultural water reuse projects in Greece, and additional 60,000 ha are being irrigated by the indirect wastewater reuse. Interestingly, only 13% of the Greek WWTPs currently adopt wastewater reuse for irrigation purposes [36].

Following Italy which was the first Southern European country to adopt a wastewater reuse guideline in 1977, Greece, Portugal and Spain have followed these legislations. According to the EU Directive 91/271/EEC subsequent national regulations (Joint Ministerial Decisions 145116/2011 and 191002/2013, regulations 145447 and 1589) are dealing with wastewater reuse issues in Greece. However, the wastewater reuse guidelines in these countries focus primarily on different parameters and different potential uses for agricultural irrigation [1,43]. Depending on the type of reuse, there are certain requirements regarding level of treatment, quality standards and monitoring policy. The Greek guideline for wastewater reuse recognizes two different types of irrigation (i) restricted irrigation (industrial and crops processed before consumption; no contact with soil and avoiding from sprinklers application), and; (ii) unrestricted irrigation (every type of crop with all possible irrigation methods) [44]. The set of limitations allows the local authority to claim an altered license for the distribution system enabling the reuse for other edible crops or flowers such as vegetables, vines and carnations, if of course the appropriate quality limits can be achieved [5]. Urban uses and groundwater recharge with direct injection require the highest effluent quality and a threshold of 2 CFU/100 mL for TC has been set. A threshold of 5 CFU/100 mL for *Escherichia coli* is set for unrestricted irrigation and industrial uses (except cooling water). Finally, the lowest quality refers to restricted irrigation, industrial cooling and aquifer recharge through basins (200 CFU/100 mL for *E. coli*). Additional barriers are included for each application, since monitoring of heavy metals and metalloids, as well as several organic compounds should be performed at a frequency depending on the population equivalents served by each WWTP [1,45]. Compared to the two benchmark guidelines (issued by the state of California and WHO), the Greek guidelines are primarily based on the California approach [1,45]. The main microbial wastewater quality indicator is *E. coli*. The risks linked to wastewater reuse and xenobiotics in the agroecological environment have been studied by Papaioannou et al. [45], Lavrnić et al. [46] and Fatta-Kassinos et al. [47]. Other studies report on the perceptions and experience of farmers regarding wastewater reuse issues, with an overall positive outcome [1,5,48,49].

Interestingly, the study of Kokkinos et al. [50] underlined the unsuitability of the Joint Ministerial Decree (JMD) on wastewater reuse in Greece and its linkage to health protection. The overall quality of the produced treated effluents was low for reuse purposes, while the performance of each one of the studied WWTPs (as it concerned microbiological, chemical parameters, etc.), after all treatment procedures was insufficient. In the vast majority, outlet samples from all three studied WWTPs were not appropriate for irrigation based on five-day biochemical oxygen demand and suspended solids limit values, set by the JMD for both limited and unrestricted irrigation applications. *Salmonella* spp., molds, Candida, helminths and human adenoviruses, were detected at high percentages in outlet samples. In accordance with previous studies, no correlations were proved between human pathogens and bacterial indicators [50].

Wastewater recycling and reuse in the Mediterranean region with a focus on policies has been reviewed by Kellis et al. [51]. Wastewater reuse planning in agriculture for the region of Western Greece, and for the Prefecture of Aitoloakarnania, has been reported by Kalavrouziotis et al. [52]. Large-scale centralized wastewater treatment systems may no longer be the most viable option for urban water management in many countries, with decentralized wastewater treatment systems serving individual or small groups of properties showing an increasing trend worldwide [10]. Stathatou et al. [53] focused on a combined natural and engineered system in the Greek island of Antiparos, for the treatment and reuse of municipal effluents, and underlined the potential of such treatment approach, especially for isolated insular and small communities [53]. Greek islands of Santorini and Thirasia have been used to assess the financial benefits of water reuse. An increase of the annual costs for optimal water and wastewater management infrastructures by 19% was estimated [54]. Borboudaki et al. [55], studied effluent management data of the Hersonissos WWTP, which is a tourist area of Crete Island and for landscape irrigation. Wastewater is principally reused for agricultural irrigation while secondary applications include fire protection and landscape irrigation.

5.2. Sludge reuse

According to the National Plan on Waste Management (CMA 49/15.12.2015/GG174A) and in correspondence with Directive 2008/98 regarding waste, the sludge disposal to landfill should have been limited to 5% by 2020. The rest 95% should have been recovered for energy production and agricultural applications. More than half (53%) of the 119,770 tons of produced sludge in 2016, was disposed in landfills. Agriculture used 33%, while 18% was used for composting or for specific applications (e.g., as fuel in cement industries) [36]. The average sludge production has been estimated at 15.3 kg dry solids per capita per year, while the average daily production of wastewater has been calculated to 210 L per capita [56].

More than half of Greece's inhabitants (total population of approximately 11 million people) live in the cities of Athens and Thessaloniki. Psyttalia wastewater treatment plant is one of the biggest WWTPs in Europe (PE coverage of 5,600,000) and is located close to the city capital of Athens. The produced sludge is anaerobically treated and is used for biogas production which covers most of the energy needs of the plant. Similarly, the sludge produced in Thessaloniki WWTP, treating 1.6×10^5 m^3/d (which serves approximately 1 million people) is anaerobically digested, thickened, dewatered, dried, and finally used as soil amendment [36].

According to a Multicriteria Decision Analysis (MCDA) for wastewater and sludge management of the WWTP of Sparta, located in southeastern Peloponnese, the best approach was their application in the agricultural area of the prefecture of Laconia, for horticultural cultivation, citrus and olive trees [57]. Wastewater and sludge from the WWTP of Agrinion, located in southwestern Greece, was used for the cultivation of forest species under greenhouse conditions [58]. Despite the progress achieved so far in Greece there are many issues which must be resolved for wastewater and sludge reuse in the context of a sustainable future development of the country [39,59–62].

6. Wastewater and sludge reuse in Israel

6.1. Nanotechnology for alleviating water quality and responding to shortage

Nanotechnology methods, based on membrane technology, can provide means of turning low quality wastewaters into a commodity that can be used without any limitations. These methods are now applied despite their high price in investment, operation and maintenance.

Main membrane systems include microfiltration, ultrafiltration, nanofiltration and reverse osmosis. These include as well different materials and the use of different concepts of energy required for systems operation. Operation of the membrane systems should be linked to adequate water quality and to clogging aspects, namely fouling due to chemical and biological processes. Field experiments conducted in the fields of the City of Arad (Israel) with raw domestic wastewater revealed the importance of utilizing the membranes. Ultrafiltration (UF) and reverse osmosis (RO) are required stages in improving the wastewater quality. Domestic wastewater includes both pathogens and dissolved solids that are removed during the use of the nanotechnology processes. The nanotechnology brings the wastewater to a level that allows it even be used for drinking purposes.

The effect of effluent quality and membrane operating regimes such as transmembrane pressure (TMP), permeate and brine flow rates, recirculation flow rates, fouling aspects influencing the growth of agriculture and crops yield are discussed [63–65]. The experiments were based on relatively large field plots (6 treatments, each of 12 by 16 m; 4 replications; duration of experiments – 4 y; each season with a different crop type however, in same plots; 6 wastewater qualities), conducted in a typical arid zone (annual precipitation around 150 mm/y). The nanotechnology system consisted of a hybrid membrane system, and total acreage of experiment was 0.6 ha. Different crops for a period of 4 y were raised every year in same plots, each in about 200 m^2. The effects of water quality were expressed mainly by the salinity, given by the electrical conductivity (EC) of the effluent which was continuously monitored [66]. During the experiment an economic analysis was conducted, examining the effects of energy consumption due to membrane fouling and related costs of flushing and calculating the efficiency of the effluent reuse [63].

6.2. Nanotechnology methods

A hybrid system with spiral wound membrane was in operation. In front of the RO system a separate component of UF membrane layout was installed [65,66]. The effluents permeate from the UF system was the feed for the RO system. This arrangement allowed removing both the pathogens and the suspended matter at the UF stage and the dissolved solids (salts) at the RO components (Fig. 1). Different combinations of UF and RO effluents were applied for irrigating the various crops each year (Fig. 2). Parallel to it, the membrane performance regarding fouling phenomena was monitored, primarily for clogging control.

Different methods and back-flushing policies were examined just to keep the membranes clean, and to allow their smooth performance [67,68]. Along with these extended experiments a series of field data was collected to examine the effects of membrane clogging on the energy demand and related operational costs.

6.3. Results

At this point only two major outcomes will be presented: the agriculture yields as being affected by the water salinity (Table 4) and the changes of membrane clogging (fouling)

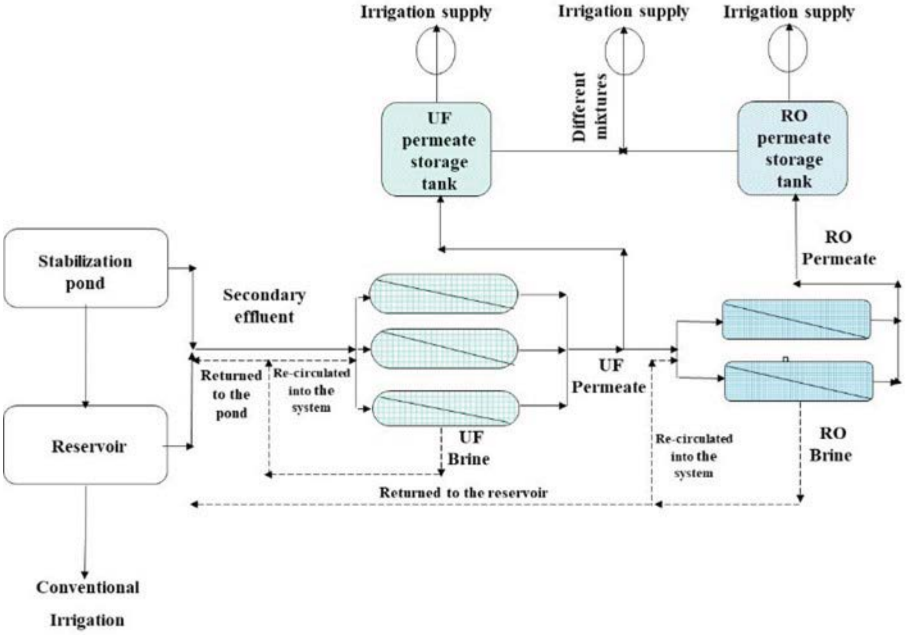
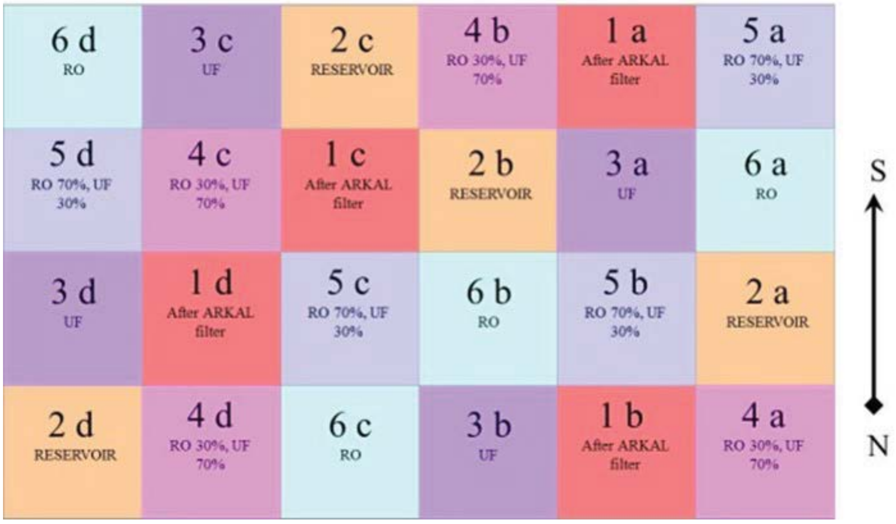


Fig. 1. Schematic description of the membrane systems for treatment of the secondary effluent.



6 d RO	3 c UF	2 c RESERVOIR	4 b RO 30%, UF 70%	1 a After ARKAL filter	5 a RO 70%, UF 30%
5 d RO 70%, UF 30%	4 c RO 30%, UF 70%	1 c After ARKAL filter	2 b RESERVOIR	3 a UF	6 a RO
3 d UF	1 d After ARKAL filter	5 c RO 70%, UF 30%	6 b RO	5 b RO 70%, UF 30%	2 a RESERVOIR
2 d RESERVOIR	4 d RO 30%, UF 70%	6 c RO	3 b UF	1 b After ARKAL filter	4 a RO 30%, UF 70%

Fig. 2. Schematic description of the experimental field layout.

and related reduction in flow rate as being affected by frequency of back flushing. Back flash was conducted with tap water accepted from the RO stage. The back flushing and the fouling rate allowed to conduct an economic analysis. As can be observed, the UF membrane removes the total suspended solids and pathogens were the RO removes the salts (dissolved solids). The results of the effluent qualities are well expressed in the corn yield which is the best with RO effluent. The highest yield was obtained for the RO treated wastewater. A high yield was also obtained for the reservoir effluent. However, this yield was obtained in the second year of the experiment where the accumulated effect of salinity was only at the initial stages of influence (Fig. 3).

6.4. Sludge

6.4.1. General issues

The total amount of disposed sludge produced in Israel (for the beginning of the year 2021) is assessed at 135,000 metric tons of dry matter per year. In usual treatment facilities the sludge is separated into two stages conducted in two separate settling basins: (i) the primarily sludge, and; (ii) the secondary stage (excess sludge). The primary sludges consist of 95% to 99.5% water and 0.5% to 5% solids. The solids content of the sludge at the final phase in the plant is around 78% to 85%, consisting of organic matter and the rest is mineral matter. Interesting is the cost of wastewater treatment in which the sludge treatment cost is around 50% of the total treatment cost.

An emerging phenomenon is associated with membrane treatment of the sludge in membrane bioreactors (MBR). Although the MBR yields high quality wastewater; one of the main problems generated is the "cake" formation on the membrane [68]. Research is conducted worldwide to solve the limiting factor of "cake" forming [69].

6.4.2. Sludge reuse

Reuse of the sludge and turning it from a nuisance into a contributing source has different faces. These alternatives depend mutually on available economic resources of the specific country. Also reuse options must take into considerations local legislation [70]. Commonly, reuse criteria of biosolids/sludge consist of two classes, although there are countries that have also a third sludge quality class (Table 5).

The first alternative refers to methane gas production rate. The calorific value of methane is around 22,000 Btu/lb. Another option is just to burn the sludge and produce energy, creating some air-pollution difficulties [71]. The combustible fractions of pyrolysis gases range from 36% to 54% for the sludge. The corresponding lower heating value range of sampled gases were 11.8 to 19.1 per m^3. Sludge

Table 4
Effluent quality parameters as accepted by the nanotechnology treatment

Location in System	BOD_5, mg/L	Total suspended solids, mg/L	Fecal coliform, CFU/100 mL	Chlorides, mg/L	Electrical conductivity, dS/m	Na, mg/L	Alkalinity, as $CaCO_3$ mg/L
Stabilization pond*	58.7	168	2.0×10^3	325	2.18	272	614
Reservoir	11.5	94	2.0×10^2	330	2.32	290	589
UF permeate	1.5	12	6	315	2.12	280	594
UF brine	195	358	3.8×10^3	325	2,23	306	588
RO permeate	0	0	0	21.5	0.14	17.6	2.4
RO brine	1.8	12	**	440	3.59	420	970

* – After a cartridge filter; ** – not monitored.

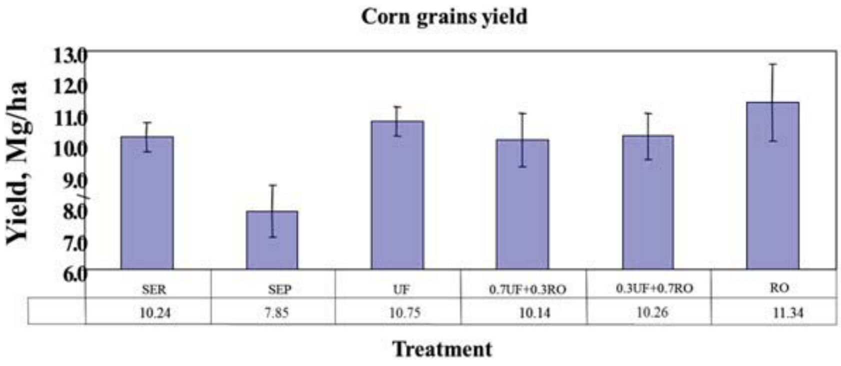


Fig. 3. The corn dry grain yield subject to different qualities of effluent, (SEP – secondary effluent from the stabilization ponds; SER – secondary effluent from the reservoir; UF-UF effluent; RO-RO effluent; 0.7UF + 0.3RO – a mixture of 70% UF effluent and 30% RO effluent; 0.3UF + 0.7RO – mixture of 30% UF effluent and 70% RO effluent).

Table 5
Classes of biosolids in which Class B contains a higher level of pathogens that Class A

Type of biosolids	Pathogen treatment	Use restriction
Class A	Treated to reduce pathogens to a very low or undetected levels	Can be applied in bulk under site restrictions or sold to the public in bags like other fertilizers
Class B	Must meet certain standards for pathogen treatment, however, can contain higher pathogen levels than Class A	Must be land applied in bulk under site restrictions

can as well be used for agricultural fertilizers. Experiments were conducted in Israel indicating that improved agricultural yields were obtained in fields fertilized with sludge [72,73]. The yields were better by around 10% in fields which received the sludge. However, the improved yields depend significantly on the combinations of nitrogen, phosphate and potassium content in the biosolids applied. Fertilizers can be considered as a "Win-Win" situation where the agriculture fields serve as acceptors for the sludge. In some areas worldwide, the farmers are even paid for the option of applying the sludge on their farms. The injection of sludge has contributive effects on the soil properties.

Sludge can be used as well for construction of buildings. Using advanced processes of squeezing the moisture and using special made forms constructing eco-blocks are the base for building materials [74,75]. These blocks are excellent isolating constructing materials. Probably there are an additional alternative to reuse the sludge.

7. Concluding remarks related to wastewater and sludge reuse in the target countries

7.1. Perú

In Perú, less than half of the produced sewage is treated and as it concerns rural areas, only a very limited percentage is covered by any wastewater treatment. Lagoons are the most widely implemented wastewater treatment technology. However, their operation is generally problematic mainly due to the mismanagement of sludge and the rarity of sludge drying bed technology application. Sludge drying is used in the State of Perú only for the big cities. Wastewater is reused for agricultural applications and for the irrigation of recreational areas, mainly in the coastal areas. Also, sludge is allowed to be reused as a soil conditioner. However, Perú does not have a comprehensive legislation for wastewater disposal and reuse, and lacks environmental quality standards and regulations for sludge management which hinders their reuse. However, the potential for further reuse of both wastewater and sludge has been identified for the country.

7.2. Philippines

Wastewater and sludge reuse are being practiced in the Philippines especially with domestic and sugar manufacturing or distillery-based wastewater. Reuse greatly enhanced soil nutrients and capacity especially in the disaster-stricken areas in Region III (Central Luzon). Yields of plants, especially sugarcane, improved the yields with the application of the biosolids. Different national and international guidelines are being followed with regards to the reuse of wastewater and biosolids.

7.3. Spain

In Spain, the reuse of effluent and sewage sludge is a widespread and largely accepted practice, basically in agriculture, although in certain circumstances there is a certain reluctance to exchange water resources. Indeed, farmers who have good quality water are not willing to lose it for the sake of a resource whose characteristics they do not know. The main uses of reclaimed water are in agriculture and golf course irrigation, while sludge is mainly used for agricultural purposes, as a fertilizer or soil amendment. There is still great potential to increase the reuse of reclaimed water, while an important part of the sludge is already used in agriculture. The latest initiatives in the country are reflected in a plan that is subject to public information (DSEAR Plan). It should be noted that the full development and implementation of the new European Regulations on agricultural reuse is pending.

7.4. Greece

A significant potential for increased uptake of water reuse solutions has been identified for Greece, since reclaimed water is currently used only to a limited scale. Most of the treated wastewater is disposed into surface water bodies and with a limited percentage (13%) of WWTPs adopting for reuse for irrigation. Interestingly, the overall quality of the produced treated effluent was found to be of low quality for reuse purposes. Decentralized wastewater treatment systems serving individual or small groups may be the ideal solution for Greece with numerous insular and small communities. Despite the overall progress achieved so far in Greece, there are many issues which must be resolved for sludge reuse. The National Plan on Waste Management, in line with Directive 2008/98, dictates the limited sludge disposal to landfill and the wide recovery for energy production and agricultural applications.

7.5. Israel

Field work was conducted in Israel, verifying that nanotechnology plays an important role in wastewater quality for reuse [76,77]. UF membranes have been used in series with RO membranes facilities. UF membranes have been used for the removal of the suspended matter and pathogens, and RO membranes for the dissolved solids (salts). This approach is mainly important in arid regions with minimal amounts of precipitation. Treated sludge can be used for diverse purposes which include agriculture, energy generation and construction. Sludge recycling depends primarily on the reliability of the product and the cost of production. Understanding, knowing the systems and prejudices are all issues which will affect the broad implementation of sludge reuse in Israel.

8. Concluding remarks

The European Commission supports the expansion and use of safe and efficient effluent technologies, emphasizing the implementation of circular economy. The recently released EU-wide framework of minimum requirements for effluent reuse is expected to reduce the pressure on water resources and enhance environmental protection, cost-effectiveness, and health safe issues of reuse. The world water market is growing by 20% every year. An increase of the interest on the "investment" in wastewater reuse is expected [8,77]. Wastewater is gaining momentum as a reliable alternative source of water, shifting the paradigm of wastewater management from 'treatment and disposal" to "reuse, recycle and resource recovery". Wastewater is no longer seen as a problem however, it is rather considered as a solution to challenges enigmas that societies are facing today [10].

It should be noted that present data is derived from the selected target countries of the study and thus can hardly provide a full picture of current conditions worldwide. The progress on wastewater and sludge research and reuse in each of the studied countries is characterized by particularities and special focus that have been given on different aspects in each country. The trends in wastewater and sludge reuse at a global scale focused on representative countries from different continents. The presentation of data from all target countries in a unified mode faced a lot of difficulties, based on available data, which was a limitation of the present study. However, the benefits of wastewater and sludge reuse have been highlighted and the updated information reflecting worldwide trends has been provided.

A wide margin for the improvement of circularity in wastewater and sewage sludge treatment and use is increasingly recognized. In the transition towards the circular economy and in the context of climate adaptation innovative solutions on wastewater and sludge reuse have a great potential to reduce the pressures on water resources [78,79]. However, the large-scale implementation of circular economy's principles for wastewater and sewage sludge requires the adoption of integrated approaches that would not focus only on its management but also on holistic innovation aspects at the technological, political, organizational, financial, and societal level.

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Supplementary information

Wastewater and sludge reuse in Perú

The Fertilizer and Pesticides Authority (FPA) and the Bureau of Agriculture and Fisheries Standards (BAFS) of the country came up with PNS/BAFS 183:2016 applying to organic fertilizers, composts and plant growth-regulators. Table S2 shows the allowable levels for heavy metals.

Based on the WHO Guidelines for the Safe Use of Wastewater, Excreta, and Greywater Volume I Policy and Regulatory Aspects, the following data shown in the Table S3 below specify the standards for wastewater and excreta in agriculture.

For agricultural irrigation using reclaimed water, the important chemical constituents to monitor are salinity, sodium, trace elements, excessive chlorine residual, and nutrients. Based on the PNS/BAFS 183:2016, the following are the standards for solid organic fertilizer, compost and liquid organic fertilizer.

Table S1
Comparison of MPL for WWTP effluents (SUNASS, 2015 modified)

Parameter			ECA and dilution factor (FD) of the necessary LMP in a natural body for environmental quality compliance								
			Category 1 A2[b]	Category 1 A3[b]		Category 1 B3[b]		Category 2 C3[b]		Category 3[b]	
		LMP	ECA	FD[a]	ECA	FD[a]	ECA	FD[a]	ECA	FD[a]	ECA
BOD_5	mg/L	100	5	20	10	10	5	10	10	15	7
DO	mg/L	200	20	10	30	7	30	–	–	40	5
TSS	mg/L	150	–	–	–	–	–	–	–	–	–
Thermotolerant coliforms	MPN/100 mL	10,000	2,000	5	20	1	200	1,000	10	2,000	5
Fats and acids	mg/L	1	20	20	1	20	–	2	10	2	12
Nitrogen NH_4	mg/L	45[c]	2	23	3.7	12	–	0.21	–	–	–
Total phosphorus	mg/L	0.15	14[c]	93	0.15	93	–	0.1	–	–	–

[a] FD = calculated dilution factor so that the effluent of the PTAR that complies with the PL can also fulfill the ECA-water.
[b] Category 1 = Population and recreational;
Subcategory A2 = Surface waters that can be treated with conventional treatment;
Subcategory A3 = Surface waters that can be purified with advanced treatment;
Subcategory B1 = Surface waters intended for recreation by primary contact;
Category 2 = Marine-coastal activities; Subcategory C3 = other activities;
Category 3 = Irrigation of vegetables and animal drinks; Irrigation of tall-stemmed vegetables.
[c] Effluent quality of a PTAR of facultative ponds considering a concentration in the tributary according to OS.090 norm and a total nitrogen removal 40% and phosphorus 30%.

Table S2
Allowable levels for heavy metals

Heavy metals	Allowable level (mg/kg dry weight) (ppm dry wt.)
Arsenic (As)	20
Lead (Pb)	50
Chromium (Cr)	150
Mercury (Hg)	2
Cadmium (Cd)	5

Table S3
Standards for wastewater and excreta in agriculture

Pathogens	Parameters
Helminth	≤1 egg per liter of restricted and unrestricted irrigation
Escherichia coli	≤10,000 per 100 mL for unrestricted irrigation to leaf crops
Escherichia coli	≤100,000 per 100 mL for unrestricted irrigation to high growing crops

Table S4
Standards for solid organic fertilizer, compost and liquid organic fertilizer

Properties	Solid organic fertilizer	Compost	Liquid organic fertilizer
Total N-P_2O_5-K_2O	5%–10%	2.5%–<5%	5%–10%
C:N	10:1–20:1	10:1–20:1	n/a
Organic matter	≥20%	≥20%	n/a
Actual moisture content	10%–35%	10%–35%	n/a
Color	Brown to black	Brown to black	n/a
Consistency	Friable	Friable	n/a
Odor	No foul odor	No foul odor	n/a