CHAPTER 11

Hydroponic System: A Promising Biotechnology for Food Production and Wastewater Treatment

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1 Introduction

Adverse climatic conditions, fast growth of world population, and industrialization have amplified the pressure on the use of conventional water sources for the different purposes (industrial activities, agriculture, and domestic use). Several regions of the world are suffering from water scarcity and available water pollution. Mediterranean countries (such as Portugal, Spain, Italy, Greece, Tunisia, Israel, and Jordan) do not meet the requirements in terms of quantity that have been increasing in the last decades for the various sectors, due to lack of water resources, winters with low rainfalls, and summers with hot and dry conditions (Prazeres et al., 2014).

Agriculture is the leading water-consuming sector (70%–80%), followed by industry and domestic use. However, industrial and domestic uses are considered priorities, conditioning the amount of accessible water for the agriculture sector (Prazeres et al., 2014). Looking for innovative and sustainable resources of water for the agricultural sector has increased considerably over several decades. Reuse of treated wastewaters coming from both industrial and domestic activities can be a sustainable and encouraging alternative to boost water supplies available not only for agriculture but also for industry. As a consequence, the use of reclaimed water should be considered in the integrated water management system to avoid damages to the environment (surface and underground water, soil, fauna, and flora) and public health. The use of wastewater for irrigation should be carefully investigated and planned in terms of proper treatment, treated wastewater quality, volume of treated wastewater used, application method, physicochemical characterization of soil, nutritional needs of plants, distance to existing water sources, risk of animal and human contamination, and others.

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Many developed and developing countries have regarded the use of domestic wastewater for different activities, for instance, in the aquaculture or agriculture (Chung et al., 2011; Rana et al., 2011). In that way, in several regions of the world, for example, North and South Africa, Mexico, South America, and southern Europe, wastewater has long been recognized as a significant supply for irrigation (Boyden and Rababah, 1996). The use of treated wastewater as an irrigation water source represents an important option in various regions of Portugal, including Santarém, Lisbon, Setúbal, Évora, Beja, and Faro (Angelakis et al., 1999). However, wastewater reuse has not been completely carried out in most regions and countries (Meneses et al., 2010).

In spite of having key contamination loads in terms of microorganisms, color, odor, solids, fats, recalcitrant organic matter, and chemical elements (Ahn and Logan, 2010; McCarty et al., 2011; Mohsen and Jaber, 2002; Mosse et al., 2013; Ochando-Pulido et al., 2013; Prazeres et al., 2013a, 2016a; Rawat et al., 2011), domestic and industrial wastewaters present high contents of biodegradable organic matter, important nutrients (calcium, magnesium, nitrogen, phosphorus, potassium, iron, zinc, copper, etc.), and water that can be used in food production, improving the growth and development of fruit-producing plants and vegetables. Domestic and industrial wastewaters can be responsible, if not properly managed, for severe environmental problems, for instance, groundwater pollution, foam generation, fast reduction of oxygen, soil salinization, alteration of soil structure, negative effect on activity and diversity of microbial community, eutrophication status, flotation of fats and solid particles, and strong odor release. Moreover, these matrices display probable threats to public health, requiring a potential risk assessment.

Environmental and economic gains can be achieved by reusing wastewater if the study, planning, and application are performed in a sustainable basis. These gains result from the fertilizer quality in terms of organic matter and nutrients (Cui et al., 2003) in the different wastewater types. Improvements of yield and the quality of the fruits and vegetables irrigated with treated wastewater have been reported in the literature. In this sense, increases of total and marketable production and fruit quality were obtained by reusing pretreated cheese whey wastewater diluted with fresh water at different ratios for irrigation of two cultivars (Roma and Rio Grande) of tomato *Lycopersicon esculentum* Mill. (Prazeres et al., 2013a,b, 2014, 2016a), representing key results for the market and consumer health. Similar findings for the yields were noted when cabbage and cauliflower plants were irrigated with treated and raw wastewater (Kiziloglu et al., 2007, 2008). Although various economic benefits are achieved in the treated wastewater reuse for irrigation, this agricultural practice can result in groundwater and surface water pollution, soil salinization, undesirable effects on the species, and accumulation of chemical constituents into the environment (Chung et al., 2011; Prazeres et al., 2013b, 2014) when performed over long periods. Accordingly, the hydroponic system is a promising agricultural and environmental biotechnology for more controlled food production and wastewater treatment and reuse, increasing the yields of the cultures and reducing the risks linked to the wastewater reuse on the soil. This agricultural and environmental biotechnology is a process based on the use of inexpensive resources of water, organic matter, and nutrients (raw or treated wastewater) for the growth and development of a complex biological system constituted by fruit-producing plants, vegetables, and beneficial microorganisms. Consequently, products (fruits or vegetables), which have economic value in the market, are generated in this complicated biological system. What is more, fruit-producing plants and vegetables capture, absorb, and accumulate several nutrients of the wastewater, enabling the wastewater treatment by a biological process. On the other hand, effluents coming from either hydroponic systems or aquaponics can still be reused in industry and agriculture.

2 Physicochemical and Biological Characterization and Problems of Different Wastewater Types

2.1 Domestic Wastewater

Table 11.1 presents the characterization of treated and raw domestic wastewater, as well as treatment applied and type of plant used for agricultural reuse. Domestic wastewater generally presents an acid and neutral pH (around 6.7–7.8), and moderate to high contents of total suspended solids (TSS of about 56–4971 mg L^{-1}) and organic matter (chemical oxygen demand-COD ≈ 300–1000 mg L^{-1}) (Alderson et al., 2015; Ayaz et al., 2015; Rana et al., 2011; Vaillant et al., 2003; Zema et al., 2012). Biodegradable organic matter measured by BOD (biochemical oxygen demand) can be found in the range from 100 to 200 mg L^{-1} (Ayaz et al., 2015; Vaillant et al., 2003). In addition, domestic wastewater displays a BOD/COD ratio within the interval of 0.28–0.41 (Ayaz et al., 2015; Rana et al., 2011). Alkalinity (as $CaCO_3$) can be found in the range of 62.1–367 mg L^{-1} (Ayaz et al., 2015; Rana et al., 2011).

Domestic wastewater also contains nutrients, such as phosphorus, nitrogen, and potassium. In this context, concentrations of total phosphorus (TP) and total nitrogen (TN) of about 3.5–9 and 30.3–41 mg L^{-1}, respectively, have been reported in literature (Vaillant et al., 2003; Zema et al., 2012). Nitrogen in domestic wastewater is present in the form of ammonium ion (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-) (Rana et al., 2011; Vaillant et al., 2004; Zema et al., 2012). Regarding potassium, Vaillant et al. (2004) referred a nutrient concentration around 15 mg L^{-1}. Consequently, raw or treated (by biological process) domestic wastewater contains some nutrients for the plant development (Ayaz and Saygin, 1996), constituting important options as fertilizers for agriculture or aquaculture (Rana et al., 2011). Cui et al. (2003) indicated that the utilization of fractions of the domestic wastewater for agricultural purposes in China is a way of soil preservation and fertilization and culture development, because this wastewater is rich in organic matter and nutrients.

Table 11.1: Physicochemical characterization, treatment applied and type of plant used for agricultural reuse of treated and raw domestic wastewater.

References	Wastewater Type	Plant Species	Treatment/ Technologies	pH	COD	BOD	TSS	TDS	TP	PO_4-P	TN	NH_4^+	NO_3^-	Cl	K	NO_2^-	Alkalinity ($CaCO_3$)
Boyden and Rababah (1996)	Primary domestic wastewater	Mignonette Green Lettuce	Primary settling tank + close-loop hydroponic-type	—	366 ± 16	195 ± 13	150 ± 10	—	6.2 ± 3	—	64	—	—	—	—	—	—
Cui et al. (2003)	Treated domestic wastewater	-	Septic tank	—	149.1	54.5	209	—	1.91	—	10.51	—	—	—	—	—	—
Cui et al. (2003)	Treated domestic wastewater	Hydroponic vegetables	Artificial soil filter	—	70.9	10.4	74.6	—	0.40	—	5.35	—	—	—	—	—	—
Vaillant et al. (2003)	Primary municipal wastewater	*Datura innoxia*	—	—	429	179	164	—	9	—	41	—	—	—	—	—	—
Vaillant et al. (2004)	Primary domestic wastewater	Wooly digitalis and foxgloves	—	—	—	—	—	—	—	8.2	—	22.7	1.1	35.9	14.9	—	—
Rana et al. (2011)	Municipal domestic wastewater (25%)[a]	Tomato (*L. esculentum*)	—	7.82	100 ± 11	60.7 ± 6.17	547 ± 43.28	269 ± 23.56	—	0.094 ± 0.011	—	0.72 ± 0.084	0.842 ± 0.091	—	—	0.005 ± 0.001	158.98 ± 9.23
Rana et al. (2011)	Municipal domestic wastewater (50%)[a]	Tomato (*L. esculentum*)	—	7.74	212 ± 17.28	90.1 ± 8.41	1581 ± 129.37	779 ± 62.38	—	0.147 ± 0.042	—	1.81 ± 0.201	7.14 ± 0.084	—	—	0.008 ± 0.001	128.99 ± 7.54
Rana et al. (2011)	Municipal domestic wastewater (75%)[a]	Tomato (*L. esculentum*)	—	7.71	307 ± 23.51	147.3 ± 11.32	3375 ± 311.27	1983 ± 153.7	—	0.182 ± 0.027	—	4.0 ± 0.53	8.13 ± 0.761	—	—	0.015 ± 0.003	124.32 ± 7.77
Rana et al. (2011)	Municipal domestic wastewater (100%)[a]	Tomato (*L. esculentum*)	—	7.49	518 ± 27.98	211.4 ± 22.37	4971 ± 437.28	3749 ± 271.31	—	0.209 ± 0.018	—	5.91 ± 0.641	8.83 ± 0.875	—	—	0.034 ± 0.005	62.1 ± 3.37

Alderson et al. (2015)	Treated domestic wastewater	—	Septic tanks	—	646	—	295	—	—	—	—	—	—	—	—	—	—
Alderson et al. (2015)	Treated domestic wastewater	—	Septic tanks + anaerobic filters	—	656	—	323	—	—	—	—	—	—	—	—	—	—
Alderson et al. (2015)	Treated domestic wastewater	—	Septic tanks + anaerobic filters + chlorination	—	299	—	66	—	—	—	—	—	—	—	—	—	—
Alderson et al. (2015)	Treated domestic wastewater	—	Facultative ponds	—	284	109	149	—	—	—	—	—	—	—	—	—	—
Alderson et al. (2015)	Treated domestic wastewater	—	Facultative ponds + maturation ponds	—	209	—	93	—	—	—	—	—	—	—	—	—	—
Alderson et al. (2015)	Treated domestic wastewater	—	Anaerobic ponds + facultative ponds + maturation ponds	—	137	50	61	—	—	—	—	—	—	—	—	—	—
Alderson et al. (2015)	Treated domestic wastewater	—	Facultative aerated ponds + facultative ponds + maturation ponds	—	188	—	94	—	—	—	—	—	—	—	—	—	—
Alderson et al. (2015)	Treated domestic wastewater	—	Upflow anaerobic sludge blanket reactors	—	266	—	131	—	—	—	—	—	—	—	—	—	—
Alderson et al. (2015)	Treated domestic wastewater	—	Upflow anaerobic sludge blanket reactors + chlorination	—	364	—	148	—	—	—	—	—	—	—	—	—	—

(*Continued*)

Table 11.1: Physicochemical characterization, treatment applied and type of plant used for agricultural reuse of treated and raw domestic wastewater. (*cont.*)

References	Waste-water Type	Plant Species	Treatment/ Technologies	pH	COD	BOD	TSS	TDS	TP	PO_4-P	TN	NH_4^+	NO_3^-	Cl	K	NO_2^-	Alkalinity ($CaCO_3$)
Ayaz et al. (2015)	Treated domestic wastewater [Period I-Summer (R:0)][b]	—	Anaerobic pretreatment + hybrid wetland system	7–7.5	—	< 14	< 14	—	—	—	—	—	—	—	—	—	—
Ayaz et al. (2015)	Treated domestic wastewater [Period II-Winter (R:0)][b]	—	Anaerobic pretreatment + hybrid wetland system	7–7.5	—	< 36	< 21	—	—	—	—	—	—	—	—	—	—
Ayaz et al. (2015)	Treated domestic wastewater [Period III-Fill-and-draw (R:0)][b]	—	Anaerobic pretreatment + hybrid wetland system	7–7.5	—	< 17	< 5	—	—	—	—	—	—	—	—	—	—
Ayaz et al. (2015)	Treated domestic wastewater [Period IV Fill-and-draw (R:1/1)][b]	—	Anaerobic pretreatment + hybrid wetland system	7–7.5	—	< 10	< 1	—	—	—	—	—	—	—	—	—	—
Ayaz et al. (2015)	Treated domestic wastewater [Period V Fill-and-draw (R:2/1)][b]	—	Anaerobic pretreatment + hybrid wetland system	7–7.5	—	< 7	< 4	—	—	—	—	—	—	—	—	—	—

Parameters expressed in mg L^{-1}, with the exception of pH.

BOD, Biochemical oxygen demand; COD, chemical oxygen demand; TDS, total dissolved solids; TN; total nitrogen; TP, total phosphorus; TSS, total suspended solids.

[a]Four different concentrations of wastewater (25%, 50%, 75% and 100%) were used.

[b]R:0—no recirculation of effluent; R:1/1 and R:2/1—correspond to recirculation of 100 and 200%, respectively.

However, it is necessary to control the microbiological characteristics for reusing municipal wastewater in agriculture (Palese et al., 2009). Rana et al. (2011) found *Escherichia coli* in raw municipal domestic wastewater, which presented a value in this microbiological parameter of 243 CFU $\times$ 10^7 mL^{-1}. These authors eliminated around 64% of this coliform bacteria population when diluting the raw domestic wastewater for a concentration of 25% with groundwater.

Reuse of domestic wastewater has been mainly conducted after application of different types of technologies, namely, primary treatment to irrigate Mignonette Green Lettuce, *Datura innoxia*, wooly digitalis (*Digitalis lanata* Ehrh.), and foxglove (*Digitalis purpurea* L.) (Boyden and Rababah, 1996; Vaillant et al., 2003, 2004), septic tank + artificial soil filter to irrigate hydroponic vegetables, such as romaine lettuce and water spinach (Cui et al., 2003). Additionally, Rana et al. (2011) studied the use of raw and diluted municipal domestic wastewater to irrigate tomato (*L. esculentum*). However, several studies have been performed to treat domestic wastewater for reusing purposes (Alderson et al., 2015; Ayaz et al., 2015). Thus, Alderson et al. (2015) studied different technologies for reusing domestic wastewater in agriculture and aquaculture, specifically, septic tanks, septic tanks + anaerobic filters, septic tanks + anaerobic filters + chlorination, facultative ponds, facultative ponds + maturation ponds, anaerobic ponds + facultative ponds + maturation ponds, aerated facultative ponds + facultative ponds + maturation ponds, upflow anaerobic sludge blanket (UASB) reactor, and UASB reactor + chlorination. These authors obtained effluents, after these sequences of treatment, with COD and TSS values in the ranges of 137–656 and 61–295 mg L^{-1}, respectively. Additionally, Alderson et al. (2015) concluded that the sequence anaerobic ponds + facultative ponds + maturation ponds is the most promising treatment line. This treatment line displayed depletions of COD, BOD, and *E. coli* of 77, 79, and 100%, respectively.

The sequence anaerobic pretreatment + hybrid constructed wetland system was investigated by Ayaz et al. (2015) to treat domestic wastewater of a small community. This study was conducted in different conditions, ranging seasons, and recirculation percentage. The system allowed a removal higher than 95% and 90% of organic matter and TN, obtaining effluents with pH values ≈ 7–7.5, contents of TSS < 1 to < 21 mg L^{-1}, BOD < 7 to < 36 mg L^{-1}, and fecal coliform number = 1,000–10,000 100 mL^{-1}. Consequently, the effluent required a disinfection step for irrigation aims.

2.2 Cheese and Dairy Wastewater

The dairy industry is aimed at the production of foods or milk-based products, such as pasteurized milk, butter, cheese, yogurt, ice cream, milk powder, and whey. For the manufacture of these products, many processes are required, which use water in the washing of equipment and facilities, heating and cooling systems, among others (INETI, 2001). In

Figure 11.1: Cheese Whey Wastewater.

this context, INETI (2001) mentioned the use of 15 L of water per liter of processed milk. Consequently, this industry is considered an important contamination source, producing many wastewater types. The generated water volume varies between 0.2 and 10 L per liter of raw milk (Vourch et al., 2008). Cheese is a major agricultural product in the world. Wastewater coming from the cheese industry is generated in an average proportion of 3–5 L for each liter of processed milk. This effluent (Fig. 11.1) is rich in organic matter, mineral salts, TSS, nutrients, oils and fats, acidity, salinity, and others. Direct discharge of these effluents into water can cause several impacts to the environment and public health (Prazeres et al., 2016b).

The raw dairy wastewater presents high concentrations of organic matter (COD ≈ 1,500–18,500 mg L^{-1} and BOD ≈ 350–12,900 mg L^{-1}), due to loss of product and raw material entrained by washing during the manufacturing process (Andrade et al., 2014; INETI, 2001; Prazeres et al., 2014, 2016a; Sarkar et al., 2006). The other characteristics of this wastewater are high concentrations of TSS (≈ 250–1600 mg L^{-1}), fats content, salinity and nutrients, such as phosphorus, nitrogen, and potassium (TP ≈ 36–110 mg L^{-1}, TN ≈ 50 mg L^{-1} and K ≈ 200 mg L^{-1}) (Andrade et al., 2014; Prazeres et al., 2014, 2016a; Sarkar et al., 2006). The pH of raw dairy wastewater is generally acid or neutral, presenting values between 3.28 and 7.5 (Andrade et al., 2014; Prazeres et al., 2014, 2016a; Sarkar et al., 2006).

For the reuse of dairy wastewater, it's necessary to apply proper treatments/technologies. Prazeres et al. (2014, 2016a) used NaOH precipitation to treat cheese whey wastewater, achieving significant removals of COD (40%), TSS (69%), turbidity (91%), sulfates (93%), total phosphorus (53%), calcium (50%), magnesium (27%), Kjeldahl nitrogen (23%), etc. After the pretreatment, the effluent was diluted with fresh water for irrigation of industrial tomato (*L. esculentum* Mill.). The treatment and dilution of cheese whey wastewater reduced the organic matter to values of COD ≈ 172–5014 mg L^{-1} and BOD ≈ 140–4450 mg L^{-1}. The solids concentration also decreased after treatment and dilution [TSS ≈ 82–265 mg L^{-1} and TDS (total dissolved solids) ≈ 82–265 mg L^{-1}]. Once the treatment and dilution were applied, the treated wastewater presented neutral pH (≈ 7.3–7.5), higher than that exhibited by the raw wastewater (pH ≈ 3.28–4.78) (Table 11.2).

Andrade et al. (2012, 2014) and Vourch et al. (2008) studied the performance of membrane technologies for the treatment and reuse of dairy industry wastewater (Table 11.2). The treatment systems comprised the nanofiltration of the effluent coming from a membrane bioreactor (Andrade et al., 2012, 2014) and storage tank + reverse osmosis (Vourch et al., 2008). In a first approach, Andrade et al. (2014) applied membrane bioreactor to raw dairy wastewater, showing high removal efficiencies for the following parameters: COD (98%), TN (86%), and TP (89%). Then, the effluent coming from the membrane bioreactor was filtrated with nanofiltration technology. The treatment system presented a total reduction efficiency of 99.9% for COD and 93.1% for total solids. Vourch et al. (2008) obtained high removal efficiencies for conductivity (97.2%–97.8%), chlorites (98.1%–98.3%), and potassium (87%–98.3%) when treating dairy wastewaters with reverse osmosis.

2.3 Olive Mill Wastewater

An olive mill has the function of receiving olives for the production of oil. For this transformation, several processes take place. The production process starts with the receipt of olives and removal of leaves and branches. Then, the olives are washed and weighed, followed by the milling, where the olives are transformed into a mass. Then, a beating phase and a centrifugation step occur under controlled temperatures. Centrifugation is a process that separates oil, water, and olive pomace (three-phase system), and oil and water + olive pomace (two-phase system). These production processes of oil require the use of water for washing olives, installations and equipments, and operation of the equipments (heating and cooling).

The production of olive oil is seasonal and has a duration of approximately 4–5 months. In this period, about 30 million m^3 of wastewater can be generated annually (Belaqziz et al., 2016; Ouzounidou et al., 2008). Generally, raw olive mill wastewater (Fig. 11.2) has an acid pH (4.5–7.2). A variable content of organic matter (COD ≈ 7.1–36,800 mg L^{-1}) and TSS (≈ 1–71,000 mg L^{-1}) is also reported. In the composition of olive mill wastewater can be also found sugars, tannins, polyphenols, polyalcohols, lipids, phytotoxic, and antibacterial phenolic substances with reduced biological degradation (Belaqziz et al., 2016; Ochando-Pulido et al., 2013; Ouzounidou et al., 2008).

To reuse this wastewater, it will have to undergo an appropriate treatment. In literature, various technologies have been applied to treat raw olive mill wastewater, such as the

Table 11.2: Physicochemical characterization, treatment applied and type of plant used for agricultural reuse of treated and raw industrial wastewater.

References	Wastewater Type	Plant Species	Treatment/ Technologies	pH	COD	BOD	TSS	TDS	TP	PO_4-P	TN	NH_4^+	NO_3^-	Cl	K	NO_2^-	Alkalinity ($CaCO_3$)
Vourch et al. (2008)	Treated dairy wastewater	—	Storage tank + reverse osmosis	—	—	—	—	—	—	—	—	—	< 2	4	5.9	—	—
Vourch et al. (2008)	Treated dairy wastewater	—	Storage tank + reverse osmosis	—	—	—	—	—	—	—	—	—	< 2	< 3	2.1	—	—
Vourch et al. (2008)	Treated dairy wastewater	—	Storage tank + reverse osmosis	—	—	—	—	—	—	—	—	—	< 2	4	4.7	—	—
Andrade et al. (2012)	Treated dairy wastewater	—	Membrane bioreactor + nanofiltration	8.99	4.0	—	—	233	—	—	—	—	—	—	—	—	166
Andrade et al. (2014)	Treated dairy wastewater	—	Membrane bioreactor + nanofiltration	—	57.3	6	—	—	1.4	—	6.9	—	—	—	—	—	—
Prazeres et al. (2014, 2016a)	Treated and diluted cheese whey wastewater (T_1-1:50)[a]	Tomato (*L. esculentum* Mill.)	NaOH precipitation	7.51 ± 0.27	172 ± 57	140 ± 49	82 ± 12	796 ± 44	—	—	—	—	—	265.9 ± 11.4	14.6 ± 2.3	—	—

Prazeres et al. (2014, 2016a)	Treated and diluted cheese whey wastewater (T_2-1:22)[a]	Tomato (*L. esculentum* Mill.)	NaOH precipitation	7.30 ± 0.29	404 ± 107	305 ± 100	100 ± 58	1043 ± 31	—	—	—	—	—	309.0 ± 11.7	24.1 ± 9.6	—	—
Prazeres et al. (2014, 2016a)	Treated and diluted cheese whey wastewater (T_3—1:10)[a]	Tomato (*L. esculentum* Mill.)	NaOH precipitation	7.32 ± 0.24	895 ± 278	738 ± 149	193 ± 34	1602 ± 198	—	—	—	—	—	421.2 ± 43.5	41.4 ± 16.1	—	—
Prazeres et al. (2014, 2016a)	Treated and diluted cheese whey wastewater (T_4—1:5)[a]	Tomato (*L. esculentum* Mill.)	NaOH precipitation	7.36 ± 0.28	1883 ± 470	1675 ± 574	265 ± 27	2899 ± 501	—	—	—	—	—	643.1 ± 106.5	73.9 ± 22.8	—	—
Prazeres et al. (2014, 2016a)	Treated and diluted cheese whey wastewater (T_5—1:2)[a]	Tomato (*L. esculentum* Mill.)	NaOH precipitation	7.43 ± 0.47	5014 ± 1481	4450 ± 1652	241 ± 47	6653 ± 1183	—	—	—	—	—	1257.4 ± 302.4	141.6 ± 59.9	—	—
Ochando-Pulido et al. (2013)	Treated olive mill wastewater	—	Fenton-like oxidation	3.2	315.9	—	141.2	—	—	—	—	—	—	1096.6	—		

(*Continued*)

Table 11.2: Physicochemical characterization, treatment applied and type of plant used for agricultural reuse of treated and raw industrial wastewater. (*cont.*)

References	Wastewater Type	Plant Species	Treatment/ Technologies	pH	COD	BOD	TSS	TDS	TP	PO_4-P	TN	NH_4^+	NO_3^-	Cl	K	NO_2^-	Alkalinity ($CaCO_3$)
Ochando-Pulido et al. (2013)	Treated olive mill wastewater	—	Fenton-like oxidation + flocculation-sedimentation	7.9	295.2	—	80.5	—	—	—	—	—	—	1095.1	—	—	
Ochando-Pulido et al. (2013)	Treated olive mill wastewater	—	Fenton-like oxidation + flocculation-sedimentation + gravel and olive stones filtration	7.7	150.8	—	13.1	—	—	—	—	—	—	990.9	—	—	
Ochando-Pulido et al. (2013)	Treated olive mill wastewater	—	Fenton-like oxidation + flocculation-sedimentation + gravel and olive stones filtration + reverse osmosis	7.6–7.7	2.3–3.7	—	0	—	—	—	—	—	0.7–0.8	15.5–20.7	1.6–2.1	—	
Belaqziz et al. (2016)	Olive mill wastewater[b]	Maize	—	4.98 ± 0.15	264430 ± 43110	—	54000 ± 1000	—	140 ± 2	3670 ± 12		1050 ± 21		3980 ± 5230	1950 ± 20		
Valderrama et al. (2012)	Treated winery wastewater	—	Conventional activated sludge	7.3	222.8	7	26	—	5.3	—	1.7	1.8	3.7	423.4	199.8		
Valderrama et al. (2012)	Treated winery wastewater	—	Membrane bioreactor	7.3	113.7	9	2.0	—	4.9	—	5.7	4.3	24.6	459.2	198.0		

Sahinkaya et al. (2008)	Treated denim textile wastewater	—	Activated sludge + nanofiltration	5.74	43	—	—	—	—	—	—	—	—	—	—		
Sahinkaya et al. (2008)	Treated denim textile wastewater	—	Activated sludge + nanofiltration	3.25	< 5	—	—	—	—	—	—	—	—	—	—		
Sahinkaya et al. (2008)	Treated denim textile wastewater	—	Activated sludge + nanofiltration	3.24	< 5	—	—	—	—	—	—	—	—	—	—		
Blanco et al. (2012)	Treated textile wastewater	—	Fenton	7.41	620	—	< 0.1	—	—	—	—	—	—	—	—		
Blanco et al. (2012)	Treated textile wastewater	—	Aerobic sequencing batch reactor + Fenton	7.36	302	—	< 0.1	—	—	—	—	—	—	—	—		
Bhuiyan et al. (2016)	Treated textile wastewater	Malabar spinach	Gamma radiation	7.1	210	140	242	960	—	—	—	—	—	—	0.024		
Mavrogianopoulos et al. (2002)	Nutrient solution prepared from diluted pig's wastewater	Giant reed (*Arundo donax*)	Open lagoon	7.6	—	—	—	—	18.61	—	—	500.06	481.20	291.80	625.03		

Parameters expressed in mg L^{-1}, with the exception of pH.
BOD, Biochemical oxygen demand; COD, chemical oxygen demand; TDS, total dissolved solids; TN, total nitrogen; TP, total phosphorus; TSS, total suspended solids.
[a] T_1, T_2, T_3, T_4 and T_5 represent the treated cheese whey wastewater diluted with fresh water in the following ratios 1:50; 1:22; 1:10; 1:5 and 1:2, respectively.
[b] Before application, this wastewater was diluted twofold.

Figure 11.2: Olive Mill Wastewater.

following sequence: Fenton-like oxidation, flocculation-sedimentation, gravel and olive stones filtration, and reverse osmosis membrane (Ochando-Pulido et al., 2013) (Table 11.2). These treatments have the purpose of reducing the content of organic matter, TSS, and other parameters, such as total phenols, total iron, fluoride, bromide, phosphate, coliform bacteria, and conductivity so that the wastewater can be reused in the olives' washing machines. On the other hand, Belaqziz et al. (2016) studied the use of olive mill wastewater coming from a traditional olive mill with a discontinuous press process (Marrakech-Loudaya, Morocco) for the maize irrigation after a two fold dilution (Table 11.2).

2.4 Winery Wastewater

The process of wine production begins with the harvesting of the fruits through hand-picking or mechanical harvester. After the grapes arrive at the winery, the branches and leaves are removed and fruits are selected to proceed in the production line. The processes used in the production depend on the type of wine intended: white, red, or rosé. However, the processes included in the wine manufacture are generally, crushing, pressing, decanting, fermentation, and clarification. Additionally, other processes can be found in the wine production, namely, maceration, malolactic fermentation, alcoholic fermentation, reassembly, bottling, and aging. These processes require the use of a lot of water; consequently, the wine production generates a high volume of wastewater. This wastewater comes mainly from washing waters and may contain stems, skins, seeds, lees, sludge, enological products used in the treatment of wine, chemicals used in washing of equipment and surfaces, and crude product waste (wine and must) (Rodrigues et al., 2006).

The harvesting period is seasonal, with an average duration of 3–4 months. The production of wastewater is intensified during the harvesting period (Amaral-Silva et al., 2016). However, some processes, such as bottling and application of enological products, take place throughout the year. The winery wastewater contains organic matter assessed by COD in the range of 13–6850 mg L^{-1} and BOD of approximately 1296 mg L^{-1}, TSS between 78 and 1230 mg L^{-1}, nutrients, for example, phosphorus and nitrogen (TP ≈ 0.95–39.5 mg L^{-1} and TN ≈ 18–55.8 mg L^{-1}), and a pH within the range of 4–8 (Amaral-Silva et al., 2016; Penteado et al., 2016; Valderrama et al., 2012).

Valderrama et al. (2012) studied the conventional treatment of activated sludge and membrane bioreactor to reuse the winery wastewater for urban service, agricultural, and recreational uses. Conventional treatment of activated sludge showed more efficient for the removal of BOD, TN, NH_4^+, NO_3^-, and Cl, compared to membrane bioreactor. This bioreactor proved to be more effective for the reduction of the following parameters: COD, TP, TSS, and K. The effluents resulting from two different processes presented neutral pH (7.3), content of TSS, COD, and BOD in the ranges of 2.0–26, 113.7–222.8, and 7–9 mg L^{-1}, respectively. Nutrients, such as phosphorus, nitrogen, and potassium are also present in the composition of the final effluent (TP ≈ 4.9–5.3 mg L^{-1}, TN ≈ 1.7–5.7 mg L^{-1}, and K ≈ 198–199.8 mg L^{-1}), as well as nitrates (NO_3^- ≈ 3.7–24.6 mg L^{-1}) (Table 11.2). The effluent of the membrane bioreactor can be reused for agricultural, urban, and recreational purposes (Valderrama et al., 2012).

2.5 Textile Wastewater

In the textile industry occurs the processing of various raw materials, natural (cotton, wool, silk, linen, etc.), manufactured using regenerated cellulose (viscose and acetate), or fully synthetic (polyester and polyamide) (INETI, 2000). The production process of the textile industry is divided into multiple stages. The process starts with the preparation of raw material, which is distinguished from natural and synthetic fibers. Natural fibers are washed, carded, and/or combed. Synthetic fibers are drawn, textured, subjected to twisting, and thermofixed. Thereafter, it follows the wiring (wire production), weaving, or knitting. The next step comprises the preparation for dyeing that includes the use of several chemicals and a large volume of water, followed by dyeing, printing, and chemical and mechanical finishing. Finally, the last stage of manufacture takes place, consisting of the production of various existing home textiles (bedding, curtains, carpets, etc.), technical textiles (tire plies, tarpaulins, etc.), and clothing (shirts, dresses, etc.), among others (INETI, 2000).

In the textile industry, it is estimated that the used water volume is in the range of 70–150 L per kg of textile product (Bhuiyan et al., 2016; Buscio et al., 2015). The effluent produced by this industry has, generally, alkaline pH (7.32–13), high temperature, considerable levels of COD (≈ 280–3000 mg L^{-1}), BOD (≈ 195 mg L^{-1}), TDS (≈ 1050–8000 mg L^{-1}), and TSS (≈ 52–310 mg L^{-1}) (Bhuiyan et al., 2016; Blanco et al., 2012; INETI, 2000; Sahinkaya et al., 2008). Additionally, these effluents contain hazardous chemicals (heavy metals, and biocides), salts, synthetic dyes, and nutrients (Bhuiyan et al., 2016; Blanco et al., 2012; INETI, 2000; Sahinkaya et al., 2008).

Textile wastewater has been treated by several processes to reuse or recycle. After treatment by irradiation (Bhuiyan et al., 2016), Fenton, aerobic sequencing batch reactor + Fenton (Blanco et al., 2012), and activated sludge process + nanofiltration (Sahinkaya et al., 2008), the characteristics of the textile wastewater were changed (Table 11.2). The pH had neutral or acidic properties (3.24–7.41), the organic matter decreased (COD < 5 to 620 mg L^{-1} and BOD ≈ 140 mg L^{-1}) and TSS presented low values (< 0.1 to 242 mg L^{-1}) (Bhuiyan et al., 2016; Blanco et al., 2012; Sahinkaya et al., 2008). Bhuiyan et al. (2016) studied the irrigation of Malabar spinach plant with textile wastewater treated by irradiation.

2.6 Pig Farm Wastewater

Pig farms comprise spaces that are intended for breeding, feeding, and housing of the animals. Most of the farms aim the growth of fattening pigs for consumption.

The properties of the pig farm wastewater may change according to the eating habits of the animals, the volume of water spent for the cleaning of stables and products used for the combating or preventing diseases (e.g., drugs given to animals) (Fridrich et al., 2014). This wastewater is composed of nitrogenous compounds (including ammonia, ammonium compounds, nitrates) (Makara and Kowalski, 2015). One of the major problems associated with pig farms is ammonia emission (NH_3), which may have negative consequences for the environment as eutrophication and acidification (Ulens et al., 2015). Additionally, this wastewater presents high organic matter monitored by COD (≈ 2334–2979 mg L^{-1}) (Yang and Wang, 1999), dark brown or black color (Fig. 11.3), and an intense odor. Another important characteristic is the acid pH (6.65–7.01) (Yang and Wang, 1999).

Mavrogianopoulos et al. (2002) studied a nutrient solution prepared after dilution of wastewater coming from an open lagoon of a pig-raising farm located in the Aliartos village (North of Athens). The diluted wastewater was used for the irrigation of giant reed plant (*Arundo donax*) in a closed gravel hydroponic system. The used nutrient solution presented the following features: neutral pH (7.6), total phosphorus (TP ≈ 18.61 mg L^{-1}), ammonium

Figure 11.3: Pig Farm Wastewater.

($NH_4^+ \approx 500$ mg L^{-1}), nitrates ($NO_3^- \approx 481$ mg L^{-1}), potassium ($K \approx 625$ mg L^{-1}), and chlorides ($Cl \approx 292$ mg L^{-1}) (Table 11.2).

3 Water Quality for Irrigation

Human activities influence the quality, availability, and impact of water in the environment. For example, the nutrient enrichment of the European water bodies represents one of the greatest current challenges (Henriques et al., 2015; Sanz and Gawlik, 2014). Agriculture, as the single largest user of freshwater on a global basis, is a major cause of degradation of surface and groundwater resources through erosion and chemical runoff. On the other hand, the water quality used for irrigation is essential for the yield and quality of crops, maintenance of the soil productivity, and protection of the environment (Quist-Jensen et al., 2015). Sustainable agriculture is one of the main challenges. Sustainability implies that agriculture not only secures a sustained food supply, but also minimizes its environmental, socioeconomic, and human health impacts (Sanz and Gawlik, 2014).

The hydroponic system is an alternative to the traditional agriculture (Caruso et al., 2011; Sigrimis et al., 2001; Tomasi et al., 2015), where the water and nutrient formulations are used to optimize crop growth, maximize yield and quality of products, and minimize costs and pollution due to effluents treatment. The composition of nutrients designed for soil cultivation is very different from that formulated for hydroponics, because plants grown in soil get most of these elements from the soil (Cavagnaro, 2016). The hydroponic nutrient solution consists of minerals in the raw water and nutrients added with fertilizers. Eventually, some organic compounds, such as iron chelates, may be present. The selection of fertilizers and their concentration in the hydroponic nutrient solution depends greatly on the quality of the raw water and the crop nutrient demand. For example, a crop-specific ceiling of Na^+ concentration is 8 mol m^{-3} for tomato and 4 mol m^{-3} for cut roses (Massa et al., 2010).

Several important factors have to be considered when preparing hydroponic nutrient solutions (Tomasi et al., 2015). Nutrients must be soluble in water. For example, nitrogen in the form of urea is not immediately available for plants in hydroponics, because urea is not soluble in water. For this reason, nitrogen must be used in its nitrate form to be utilized in hydroponics. Additionally, pH influences the solubility of nutrients in the hydroponic solution or soilless growing substrate, specifically for metal micronutrients. In the soilless plant production, pH is affected by several parameters, namely, water characteristics (alkalinity), incorporation of mineral and organic compounds, plant species, nitrogen form, nutrient content, acidity, and cation exchange capacity of the substrate (Dickson et al., 2016). On the other hand, the water quality used for the preparation of nutritive solutions plays an important role in the final salinity, potential harmful, required nutrients, concentration of elements, such as sodium, chlorides and boron, pH, and uptake of nutrients by plants (Neocleous and Savvas, 2016).

3.1 Control of Irrigation and Nutrient Supply

In closed hydroponic systems, the same nutrient solution is recirculated and the nutrient concentrations are monitored and adjusted. Contrarily, in open hydroponic systems, a fresh nutrient solution is introduced for each irrigation cycle. The drainage water from these greenhouses is generally released into the local environment, causing pollution concerns. Grewal et al. (2011) showed that the recycling of the drainage water resulted in a 33% reduction in potable water used for irrigation in cucumber production. The drainage water still contained N 59%, P 25%, and K 55%, relatively to the initial amount applied. These amounts illustrated the potential for nutrient recovery and production cost savings through the reuse of drainage water. Recycling of drainage water can considerably improve sustainability of low-cost hydroponic greenhouses and help minimize the environmental footprint of the greenhouse industry.

When irrigation water has poor quality, in general, closed systems are not financially viable under strict environmental rules and the most valuable strategy is likely the improvement of water quality (Massa et al., 2010). Closed growing systems, where the drainage water is captured and reused after nutrient replenishment, can reduce the consumption of water and fertilizers and the environmental pollution that are generally associated with overirrigation (Massa et al., 2010). Open (free-drain) soilless cultures are more commonly used for vegetable and ornamental crops, since the management of fertigation is much simpler in these systems (Massa et al., 2010). In a semiclosed system, the nutrient solution is normally recirculated until the electrical conductivity (EC) and/or the concentration of some potential toxic ions reach a maximum acceptable threshold value - after it is replaced, at least partially.

Greenhouse operations require precise control of irrigation and nutrient supply to optimize the crop growth and minimize the cost and pollution of the effluents (Sigrimis et al., 2001). In modern greenhouses, nutrient supply is computer controlled and based on the measuring of salinity, compensating deficiencies using a mix of clean water and two or more stock nutrient solutions. At the same time, the drain water flow from the crop is measured using an appropriate flow sensor. A nutrient solution strength of 1.3 dS m^{-1} EC should be preferred during the spring season, whereas a 2.2 dS m^{-1} EC proved to be the best in the winter in terms of fruit quality when alpine strawberry (*Fragaria vesca* L.) was grown in hydroponics with the nutrient film technique (NFT) (Caruso et al., 2011).

The measurements of greenhouse climate could be a good methodology for irrigation control and nutrient supply by using a model based on water losses by transpiration (Sigrimis et al., 2001). Additionally, the redox potentials (Eh) could be used for extended periods to control the nutrient uptake (Lissner et al., 2003). The relationship between pH and Eh was found to be linear, with a pH change of one unit for every 50 mV change in Eh. *Cladium jamaicense* and *Typha domingensis* produced less biomass at low Eh and the effect of Eh was modified by phosphate availability (Lissner et al., 2003).

3.2 Raw Water Quality

The irrigation water can come from rainwater, groundwater (extracted from springs or by using wells), surface water (withdrawn from rivers, lakes, or reservoirs), or nonconventional sources, such as treated wastewater, desalinated water, or drainage water. The treated wastewater sources constitute the municipal water supplies, gray-water, agricultural, and industrial process wastewaters. For this purpose, water quality is based on concentrations of specific ions and phytotoxic substances that are relevant for the plant nutrition. The key properties of the irrigation water quality constitute total soluble salt content, the concentration of specific ions (e.g., Ca, Mg, K, and P), the concentration of substances that can become toxic (e.g., Zn), and the ratio of bicarbonate to calcium and magnesium (Schwarz et al., 2005). Currently, 17 elements are considered essential for most plants, namely, carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, copper, zinc, manganese, molybdenum, boron, chlorine, and nickel. The nutrient composition determines EC and osmotic potential of the solution.

3.2.1 Groundwater

The groundwater supplies may come from springs and wells, and the quality is usually good. The groundwater presents high dissolved solids concentration and low TSS. Contrarily, the surface water presents TSS, high organic matter content, and low salinity. For the groundwater bodies of the European Union (EU), 87% hold a good quantitative status and 80% achieve a good chemical status. The most frequent cause of poor groundwater chemical status is excessive nitrates (Henriques et al., 2015).

3.2.2 Surface water

The first cycle of river basin management plans provide information to assess the status of the European water bodies and to identify the major causes of water management issues. The surface water bodies with good or high ecological status are limited to 42% across the EU. This is mainly due to the following: (1) nutrient enrichment from agricultural diffuse sources (in 40% of rivers and coastal waters and in 33% of lakes and transitional waters) and point source discharges (in 22% of the water bodies); (2) hydrological and geomorphological pressures causing altered habitats (in 40% of rivers and transitional waters and in 30% of lakes), mainly attributable to hydropower, navigation, agriculture, flood protection, and urban development (Henriques et al., 2015).

Emerging organic contaminants (EOCs), such as pharmaceuticals and personal care products (PPCPs) have been detected in surface water used for irrigation in agriculture (Hurtado et al., 2016). Batavia lettuce (*Lactuca sativa*) grown under controlled conditions was irrigated with EOCs (e.g., nonsteroidal antiinflammatories, sulfonamides, blockers, phenolic estrogens, anticonvulsants, stimulants, polycyclic musks, biocides) at different concentrations (0–40 $\mu g\ L^{-1}$). Linear correlations were obtained between the EOCs concentrations in the roots and leaves and the irrigation concentrations for most of the contaminants investigated.

3.2.3 Water reuse

The chemical composition of treated wastewater depends on the origin and the treatment received (Sanz and Gawlik, 2014). Effluents from nonindustrial municipalities that have received at least secondary treatment present generally low concentrations of heavy metals, which do not cause adverse effects on plant growth and public health. However, these effluents contain suspended and dissolved organic and inorganic solids. Conventional treatment plants have higher removal efficiency of BOD, but lower removal efficiency of TN and TP (Adrover et al., 2013). Treated wastewaters contain nutrients that are useful for plants growth and help to reduce fertilizer needs. Additionally, wastewater can have pollutants that cause adverse effects on plants and public health. Most of them presently have no regulations: solvents, beta-blockers, antiepileptics, veterinary and human antibiotics, oral contraceptives, household chemicals, and food additives (Adrover et al., 2013).

Oils, greases, cellulose, and lignin can cause anoxic conditions in aquatic ecosystems. Additionally, macronutrients (N, P, and K) and metals (Cd, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Zn, etc.) can promote toxicity, nutrient imbalance, pest and disease in plants. The micronutrients (B, Ca, Cu, Fe, Mg, Na, Co, etc.) can lead to plant toxicity (Sanz and Gawlik, 2014). On the other hand, inorganic salts (Cl, S, NO_3^-, etc.) cause plant osmotic stress and human health risks (methemoglobinemia associated to excess of nitrates) (Sanz and Gawlik, 2014).

Table 11.3 summarizes the main characteristics of the water quality for closed hydroponic system, desalinated sea water, rain water, standard nutrient solution, domestic wastewater treated by secondary treatment, treated cheese whey wastewater after chemical precipitation with lime and carbonation reactions with atmospheric CO_2, and treated vinasse by decantation and filtration. The rainwater is the best water to prepare the nutritive solution, because all parameters are according to the rules of water quality for closed hydroponic systems (Schwarz et al., 2005). The desalinated seawater (Martínez-Alvarez et al., 2016) could contain excess sulfates and conductivity. On the other hand, all treated wastewaters (Table 11.3) present nutrients that can be used by plants, reducing the required commercial nutrients. The excess of conductivity can be solved by dilution with water coming from different origins. The agro-industrial wastewaters contain a lot of nutrients and organic matter. The use of these treated wastewaters in hydroponic systems, as a nutritive solution, could be an interesting solution for reducing fertilizer needs and simultaneous wastewater tuning with the use of nutrients to produce foods. The semiclosed systems could be a good solution for tuning the agro-industrial wastewaters, because the nutrient solution is recirculated till the nutrients concentration reaches a minimum value and afterward it is replaced. Finally, it can still be used as irrigation water or discharged in receiving waters.

Vinasse is the largest pollution source of the ethanol industry, being removed from the base of distillation columns. It is a strong, saline, and dark colored effluent with high COD and a large amount of mineral nutrients essential for plant growth (Santos et al., 2013). Vinasse is produced in an average amount of 12–15 L for each liter of generated alcohol. A nutritive solution prepared using 10% of vinasse decanted, filtered, and supplemented with nutrients was used in a NFT hydroponic system (Table 11.3). A suitable growth of the lettuce, watercress, and rocket production was observed (Santos et al., 2013). This technology could be an alternative to vinasse management. Another example was used for the growth of purslane that is a native terrestrial plant in the Mediterranean region and considered weeds because it reproduces spontaneously and easily. It can be grown in any type of soil, ideally in a mild, deep, fertile, and well-drained soil; rich in organic matter, with a pH between 5.5 and 7. After treatment by chemical precipitation and carbonation reactions with atmospheric CO_2, cheese whey wastewater, free of total coliforms, was used as a nutritive solution in the crop of purslane (*Portulaca oleracea* L.) in a NFT hydroponic system, without any supplementation of nutrients (Caeiro, 2015).

Table 11.3: Quality of raw water and nutrients solution.

Parameters	Raw Water			Nutrients Solution			
	Water for Closed Hydroponic Systems (Schwarz et al., 2005)	Desalinated Sea Water (Martínez-Alvarez et al., 2016)	Rain Water (Ruas, 2012)	Half Strength Hoagland Nutrient Solution (Adrover et al., 2013)	Treated Domestic Wastewater (Adrover et al., 2013)	Treated Cheese Whey Wastewater (Prazeres et al., 2016b)	Treated Vinasse (Santos et al., 2013)
pH	—	6.9–8.3	6.6 ± 0.1	6.2	7.9–8.1	7.92 ± 0.01	—
EC (dS m^{-1})	307 ± 138	0.2–0.58	0.503 ± 0.012[b]	1.15	1.50–1.60	3.73 ± 0.03	—
TSS (mg L^{-1})	—	—	5 ± 4	0	28–64	—	—
NO_3^- (mg L^{-1})	—	—	3.4 ± 0.5	113	0.2–10	—	648.36
NH_4^+ (mg L^{-1})	—	—	0.38 ± 0.01	14	12–18	1.3 ± 0.3[c]	24.18
TP (mg L^{-1})	—	—	230.9 ± 2.2	31.0	1.9–2.8	0.6 ± 0.3	161.92[d]
K (mg L^{-1})	—	—	2.1 ± 0.1	197	15–18	81.7 ± 4.6	368.85
Na (mg L^{1})	—	9–86	2.9 ± 1.6	0	85–96	1042 ± 16	0.75
Ca (mg L^{-1})	46.5 ± 34.0[a]	—	< 2	60	31–50	152.2 ± 8.5	274.45
Mg (mg L^{-1})	41.8 ± 31.4[a]	0–5.5	5.3 ± 0.5	28	11–12	11.9 ± 5.2	49.14
SO_4^{2-} (mg L^{-1})	52.1 ± 0[a]	0–80	—	—	—	—	302.1
B (mg L^{-1})	—	0.2–0.71	—	—	—	—	1.94[e]
Fe (mg L^{-1})	7.31 ± 19.9[a]	—	—	0.5	—	—	2.792
Cu (mg L^{-1})	—	—	—		—	—	0.06
Zn (mg L^{-1})	6.71 ± 3.95[a]	—	—	—	—	—	0.27
Alkalinity (mg L^{-1} $CaCO_3$)	—	12.7–85	—	—	—	—	—
HCO_3^- (mg L^{-1})	61.1 ± 43.6[a]	—	—	—	—	—	—
SAR	—	0.35–6.80	—	—	—	—	—

EC, Electrical conductivity; SAR, sodium adsorption ratio; TP, total phosphorus; TSS, total suspended solids.
[a]As µmol L^{-1}.
[b]As µS m^{-1}.
[c]As NH_3.
[d]As PO_4.
[e]As BO_3.

4 Wastewater Reuse and Treatment by Hydroponic System for Food Production

As mentioned previously, domestic and industrial wastewaters constitute a difficult subject from both environmental and public health viewpoints. These wastewaters present high contents of organic matter (COD and BOD), solids, oils and fats, chemical elements (phosphorus, nitrogen, calcium, magnesium, chloride, sodium, potassium, aluminum, heavy metals, etc.), and, sometimes, a problematic salinity level according to the wastewater type (Calheiros et al., 2012; Huang et al., 2014; Ioannou et al., 2013; Khoufi et al., 2009; Kim et al., 2016; McCarty et al., 2011; Mohsen and Jaber, 2002; Mosse et al., 2013; Ochando-Pulido et al., 2013; Oller et al., 2011; Prazeres et al., 2016b; Rawat et al., 2011; Saddoud and Sayadi, 2007). Thus, the selection of the optimal processes that make up the treatment line for the different wastewater types is a complex question. It is important that the processes of wastewater treatment enable not only the contamination reduction, but also the valuable products generation.

Environmental Protection Agency (EPA) has recommended the wastewater treatment and reuse for the contamination management and control in the diverse water resources (EPA and AID, 2004), playing an essential role in the sustainable water use. Agricultural reuse of domestic and industrial wastewaters can be an important strategy for the wastewater pollution control, water scarcity management and reduction of the commercial fertilization, because the wastewater could provide the water and nutrients (Ca, Mg, N, P, K, etc.) required for the growth and development of cultures (Boyden and Rababah, 1996) either in soil or in hydroponic systems.

The wastewater reuse has been mainly conducted using domestic/urban effluents (Asano et al., 1996; El Ayni et al., 2011; Chung et al., 2011; De Sanctis et al., 2016; Kiziloglu et al., 2008; Lyu et al., 2016; Meneses et al., 2010; Ofosu-Asiedu et al., 1999; Zema et al., 2012). However, some studies have also been performed for the reuse of industrial effluents (Bhuiyan et al., 2016; Blanco et al., 2012; Graber and Junge, 2009; Guillaume and Xanthoulis, 1996; Lyu et al., 2016; Mahmoud et al., 2010; Mavrogianopoulos et al., 2002; Ofosu-Asiedu et al., 1999; Prazeres et al., 2013a, 2014, 2016a; Sahinkaya et al., 2008). In this context, the generation of 5.3 t of BOD d^{-1} was expected coming from food industries by Mohsen and Jaber (2002), of which about 60% were employed for irrigation aims.

The application of wastewater on soil is an ancient practice. Thus, several studies have been conducted with this purpose. Reuse of pretreated cheese whey wastewater diluted with freshwater, at five different levels of salinity, for the irrigation of tomato crops *L. esculentum* Mill. (Roma and Rio Grande) was successfully performed (Prazeres et al., 2013a,b, 2014, 2016a). In such studies, increased soluble solids content, epidermis firmness, and fruit fresh weight were obtained, as well as the depletion of the yield losses with epidermis deformation owing to solar exposition. The increment of the nutritional value of fruits obtained by reusing pretreated cheese whey wastewater was also successful, improving the concentrations of lycopene (25%–44%), total proteins (17%–21%), potassium (13%–25%), and reducing sugars (14%–40%) (Prazeres et al., 2013c).

Kiziloglu et al. (2007) accomplished several irrigation experiments, comprising trials with raw wastewater, preliminary, and primary treated wastewater to develop cabbage plants (*Brassica olerecea* var. Capitate cv. Yalova-1). These authors observed a significant effect of the wastewater irrigation on physicochemical characteristics of the soil, yield, and mineral compositions of the plants. The irrigation using wastewater allowed to improve the yield to values in the range from 2950 ± 55.0 (plants irrigated with primary treated wastewater) to 3510 ± 54.2 kg ha^{-1} (plants irrigated with raw wastewater), compared to control (2780 ± 42.1 kg ha^{-1}). Regarding the mineral composition, the irrigation with raw wastewater led to a higher content of N, P, K, Fe, Mn, Zn, Cu, B, and Mo in cabbage plants. Additionally, increments of salinity, organic matter, cation exchange capacity, exchangeable bases (Ca, Mg, K, and Na), total nitrogen, available phosphorus and microelements (Fe, Mn, Zn, Cu, B, and Mo) were noted in the soil characterization when applying wastewater. Comparable effects were obtained by Kiziloglu et al. (2008) when studying the irrigation of cauliflower (*B. olerecea* L. var. botrytis) and red cabbage (*B. olerecea* L. var. rubra) plants with raw and treated (preliminary and primary treatments) wastewater, compared to groundwater irrigation.

Treated domestic wastewater arising from domestic sewage treatment plants of Jeonju-si, (Jeollabuk-do, Republic of Korea) has been also applied for the growth and development of brown rice (*Oryza sativa* L.) during 3 years in a soil with loam texture, average pH around 6.28 ± 0.42, organic matter of about 29.5 ± 9.1 g kg^{-1}, and contents of available phosphorus and total nitrogen of 189.1 ± 18.4 and 1092.0 ± 98.5 mg kg^{-1} (Chung et al., 2011), respectively. In this study, treatment of domestic wastewater was composed of mechanical screen, grit removal tanks, primary sedimentation, extended aeration, sedimentation, and chlorination. The soil irrigation using treated domestic wastewater resulted in raising the concentrations of heavy metals, such as Pb, Cd, Cu, and Zn for both soil and brown rice, compared to groundwater irrigation. Nonetheless, the brown rice presented heavy metals concentrations that did not exceed the recommended tolerable levels. Increases of P_2O_5 concentrations in brown rice composition were also obtained when reusing treated domestic wastewater. Additionally, the concentrations of total nitrogen, crude protein, and amylose in the brown rice composition were not significantly influenced by the reuse of treated domestic wastewater.

The application of wastewater on the soil, in the long term, may be connected to the contamination of groundwater and degradation of soil structure owing to the presence of chemical elements and salinity level of wastewater. This soil quality degradation can affect the crop yield, fruit quality, plant development, and growth (Glover, 2001; Mapanda et al., 2005; Prazeres et al., 2013b, 2014; Travis et al., 2010). Furthermore, the accumulation of chemical contaminants into the ecosystems results in a major risk to the public health (Chung et al., 2011). In this context, Kiziloglu et al. (2007) emphasized the accumulation of heavy metals, for instance, cadmium, copper, iron, manganese, lead, and zinc coming from the domestic and industrial wastewater irrigation. Consequently, wastewater reuse in agriculture through hydroponic systems can be an interesting opportunity to avoid environmental and public health impacts. These systems have been widely applied for the production of various types of vegetables and fruits. In hydroponic systems, plants develop with the roots immersed in a liquid or maintained through inert substrate within tanks supplied with commercial solutions of nutrients.

When wastewaters are used in hydroponic systems as nutrient solutions, two significant advantages are accomplished, explicitly, providing nutrients needed for the development and growth of fruit-producing plant and vegetables that have commercial value in the market, and the wastewater treatment and management with depletion of organic matter and nutrients by means of a biological process (Rana et al., 2011). Contrary to hydroponic process, wetland treatment systems use plants with restricted commercial importance for the contamination reduction of wastewater (Comino et al., 2013; Vaillant et al., 2003).

Table 11.4 summarizes some studies found in the literature for the wastewater treatment using hydroponic and aquaponics systems. Boyden and Rababah (1996) obtained high removal efficiencies when treating settled primary domestic wastewater, coming from the sewage treatment plant of Liverpool, by commercial hydroponic system, with substrate of perlite and vermiculite, for the growth of Mignonette Green lettuce, using a commercial nutrients solution as a control. These authors achieved depletions of organic matter (COD ≈ 86% and BOD ≈ 87%), TSS (99%), and nutrients, such as TP (77%) and TN (80%) in the wastewater composition. However, the development, growth, and yield of the culture were negatively affected by the use of wastewater, owing to the low potassium concentration and trace element presence. Thus, Boyden and Rababah (1996) reported a reduction of about 50% on the lettuce yield when plants were irrigated with settled primary domestic wastewater, compared to the control. Similar results in terms of removal efficiencies were found by Vaillant et al. (2003) when primary municipal wastewater was treated by means of *D. innoxia* plants in a NFT commercial hydroponic system with horizontal flow. In this study, COD, BOD, TSS, and NH_4^+ were effectively removed by the plants with reductions of 82, 91, 98, and 93%, respectively. TP was also reduced; nevertheless, this nutrient only presented a percentage of removal around 38%. Vaillant et al. (2003) did not detect significant differences in the plant behavior resulting from the primary municipal wastewater reuse, namely, plant dry weight, growth rate, shoot dry weight/root dry weight, ratio of variable fluorescence over maximal fluorescence, and photochemical efficiency of photosystem II.

Septic tank domestic wastewater (after an artificial soil filter process) was also treated applying a hydroponic system by Cui et al. (2003) for the development of two vegetable types, to be precise, romaine lettuce and water spinach. Differences in the behaviors related to vegetables were found according to the plant type. Higher efficiencies were obtained for the romaine lettuce compared to the water spinach. Biological process using romaine lettuce

Table 11.4: Hydroponic and aquaponics system for water treatment.

Parameters	Boyden and Rababah (1996)	Vaillant et al. (2003)	Cui et al. (2003)	Cui et al. (2003)	Graber and Junge (2009)	Graber and Junge (2009)	Graber and Junge (2009)	Graber and Junge (2009)	Graber and Junge (2009)	Graber and Junge (2009)	Rana et al. (2011)
System type	Commercial hydroponic system (close-loop)	NFT commercial hydroponic system (horizontal flow)	Hydroponic system	Hydroponic system	Conventional hydroponic system (continuous water flow)	Conventional hydroponic system (continuous water flow)	Conventional hydroponic system (continuous water flow)	Aquaponics system, recirculating aquaculture systems–RAS (continuous water flow)	Aquaponics system, recirculating aquaculture systems–RAS (continuous water flow)	Aquaponics system, recirculating aquaculture systems–RAS (continuous water flow)	Aquaponics
Filling material	Perlite/vermiculite (ratio = 2 perlite: 1 vermiculite)	—	—	—	Light expanded clay aggregate (LECA)	Light expanded clay aggregate (LECA)	Light expanded clay aggregate (LECA)	Light expanded clay aggregate (LECA)	Light expanded clay aggregate (LECA)	Light expanded clay aggregate (LECA)	Floating bed (pulp-free coconut fiber)
Wastewater type	Settled primary domestic wastewater	Primary municipal wastewater	Domestic wastewater[b]	Domestic wastewater[b]	Tap water + fertilizer	Tap water + fertilizer	Tap water + fertilizer	Fish wastewater	Fish wastewater	Fish wastewater	Municipal domestic wastewater[c]
Plant	Mignonette Green Lettuce	*D. innoxia*	Romaine lettuce	Water spinach	Tomato	Eggplant	Cucumber	Tomato	Eggplant	Cucumber	Tomato (*L. esculentum*)
COD removal (%)	86	82	37.36	25.28	—	—	—	—	—	—	20–61.38
BOD removal (%)	87	91	82.31	42.77	—	—	—	—	—	—	61.61–72.03
TSS removal (%)	99	98	89.42	68.96	—	—	—	—	—	—	—
TP removal (%)	77	38	47.62	23.81	37	9	48	—	5	27	62.76–74.83[d]
TN removal (%)	80	93[a]	66.76	57.91	34	25	36	69	9	17	74.7–78.03[e]
K removal (%)	—	—	—	—	28	16	25	—	—	—	—

BOD, Biochemical oxygen demand; COD, chemical oxygen demand; TN, total nitrogen; TP, total phosphorus; TSS, total suspended solids.

[a]As NH_4^+.

[b]After an artificial soil filter process.

[c]Four different concentrations of wastewater (25, 50, 75, and 100%) were used.

[d]As PO_4^{3-}.

[e]As NO_3^-.

was able to eliminate approximately 82% of BOD and 89% of TSS, compared to a 43% BOD removal and a 69% TSS depletion for hydroponic system with water spinach. Hydroponic systems with romaine lettuce also showed a good performance in removing COD (37%), TP (48%), and TN (67%). Cui et al. (2003) also reported the effects of using septic tank domestic wastewater (after an artificial soil filter process) on the romaine lettuce quality in terms of weight of fresh stem per each stem, nitrate, vitamin C, coarse protein (in dry matter), and soluble sugar, compared to hydroponic system with nutrient solution in greenhouse and soil cultivation in field. Hydroponic system fed with nutrient solution exhibited a higher vegetable production (119.42 g of fresh stem per each stem) compared to the hydroponic system fed with treated effluent (88.59 g of fresh stem per each stem) and soil cultivation (81.57 g of fresh stem per each stem). Nonetheless, the contents of vitamin C, coarse protein (in dry matter) and soluble sugar in the lettuce irrigated with treated effluent showed no significant differences compared to the hydroponic system fed with nutrient solution and soil cultivation in field. In addition, a significant benefit observed by Cui et al. (2003) was the lowest nitrate concentration in the lettuce grown in hydroponic system supplied with treated effluent (237.6 g kg^{-1} of nitrate) compared to the hydroponic system fed with nutrient solution (378.6 g kg^{-1}) and soil cultivation (301.0 g kg^{-1}).

Cheese whey wastewater treated through chemical precipitation and carbonation reactions with atmospheric CO_2 was applied as a nutritive solution in the crop of purslane (*P. oleracea* L.) in a NFT hydroponic system (Caeiro, 2015). The COD of treated cheese whey wastewater was in the range of 11–347 mgL^{-1}. The results showed that fresh and dry weight of shoot, fresh and dry weight of roots, leaf area, dry matter of leaves and roots presented similar values to those obtained when using a commercial nutritive solution. The COD was removed close to 100%. Using a nutritive solution from pretreated cheese whey wastewater for lettuce growth, it was confirmed that the plants obtained the required nutrients and played an important role in the system, once it worked as a tuning process. In the nutrient solution from pretreated cheese whey wastewater, the final effluent could be discharged into the aquatic environment at the end of each cycle (Rodrigues, 2015).

The treatment and reuse of wastewater have been also studied by aquaponics, using vegetables or fruit-producing plants (Endut et al., 2010; Graber and Junge, 2009; Rana et al., 2011). Graber and Junge (2009) studied an aquaponics system (recirculating aquaculture systems—RAS) of continuous water flow that was filled with light expanded clay aggregate (LECA), compared to a conventional hydroponic system fed with tap water and fertilizer. In this study, tomato, eggplant, and cucumber were used to treat and reuse fish wastewater through aquaponics system or remove nutrients by hydroponic system. Hydroponic process indicated better operation for the removal of nutrients than the aquaponics system, except for the removal of nitrogen by means of tomato plants. In the hydroponic system, eggplant revealed the worst efficiencies taking into account the following parameters: TP, TN, and K. Tomato and cucumber were more efficient than eggplant when growing in hydroponic system, presenting depletion efficiencies in the range of 37%–48%, 34%–36%, and 25%–28% for TP, TN, and potassium, respectively. Consequently, tomato (389 g FW m^{-2} d^{-1}) and cucumber (125 g FW m^{-2} d^{-1}) showed higher fruit yields in a hydroponic system than in aquaponics system (355 and 80 g FW m^{-2} d^{-1} for tomato and cucumber, respectively).

Rana et al. (2011) assessed the aquaponics system performance to treat municipal domestic wastewater by tomato plants (*L. esculentum*) grown on floating bed of pulp-free coconut fiber. In that study, four different concentrations of wastewater (25, 50, 75, and 100%) were used and compared to groundwater (control trial). Aquaponics system proved to be very effective in removing COD, BOD, phosphate and nitrate, showing removals within the intervals of 20%–61%, 62%–72%, 63%–75%, and 75%–78%, respectively. Additionally, aquaponics system was also effective for the removal of *E. coli* (91%–92%). Growth and development of tomato plants were improved when using aquaponics system fed with municipal domestic wastewater, presenting an average crop yield in the range from 32 to 125 g $plant^{-1}$, according to the concentration of wastewater. However, a disadvantage related to the accumulation of Pb and Cr in the tomato crop higher than the safe level was observed when aquaponics was used to treat municipal domestic wastewater and cultivate fruit-producing plants.

Usually, organic matter and nutrients cannot be removed completely by hydroponic or aquaponics systems (Boyden and Rababah, 1996; Cui et al., 2003; Rana et al., 2011; Vaillant et al., 2003), remaining a recalcitrant contamination to this biological treatment process in the final effluent. In this context, Saxena and Bassi (2013) reported that hydroponic effluents present high contents of phosphorus and nitrates. A similar finding was reported by Park et al. (2008) in relation to the nitrate content. Consequently, hydroponic effluents may require the application of a posttreatment to reduce contamination to values imposed by legislation. The treatment of hydroponic effluents has also been the subject of study through denitrification filters with supplementation of organic carbon source (pretreated plant liquors) (Park et al., 2008), hybrid denitrification filter in laboratory scale (Park et al., 2009), constructed wetlands (Gagnon et al., 2010), alkali precipitation + cultivation system with marine algae *Dunaliella salina* (UTEX 1644) (Saxena and Bassi, 2013).

5 Conclusions

Wastewater reuse is an important strategy to minimize the water shortage existing in various regions of the world. The use of treated wastewater for agricultural irrigation brings significant economic and environmental benefits. Domestic and industrial wastewaters are important alternatives to supply the nutrients required for the production of fruits and vegetables through the soil application or hydroponic system. The wastewater reuse for irrigation through hydroponic system avoids the surface water and groundwater contamination and soil salinization. Additionally, this option allows the reduction of the commercial fertilizer application, development of vegetables and fruit-producing plants, and utilization of low-cost water sources. Plants, such as Mignonette Green and romaine lettuce, *D. innoxia*, water spinach, tomato, eggplant, and cucumber have shown capacity to grow in hydroponic and aquaponics system supplied with wastewater or nutrient solution to produce valuable products and reduce organic matter measured by COD (20%–86%) and BOD (43%–91%), TSS (69%–99%), and nutrients, such as P (5%–77%), N (9%–80%), and K (16%–28%) of domestic/municipal and fish wastewater or nutrient solutions (Boyden and Rababah, 1996; Cui et al., 2003; Graber and Junge, 2009; Rana et al., 2011; Vaillant et al., 2003). However, several types of agro-industrial and industrial wastewater remain unexploited as sources of water, organic matter, and nutrients for hydroponic systems composed of fruit-producing plants and vegetables. Similarly, the agro-industrial and industrial wastewater treatment has been poorly investigated by this complex biological system. The wastewater reuse by hydroponic system should be carefully planned and monitored to prevent human contamination through microorganisms and/or chemical elements.

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Abbreviations

BOD Biochemical oxygen demand
COD Chemical oxygen demand
EC Electrical conductivity
Eh Redox potentials
EOCs Emerging organic contaminants
EPA Environmental Protection Agency
EU European Union
LECA Light expanded clay aggregate
NFT Nutrient film technique
PPCPs Pharmaceuticals and personal care products
RAS Recirculating aquaculture systems
SAR Sodium adsorption ratio
TDS Total dissolved solids
TN Total nitrogen
TP Total phosphorus
TSS Total suspended solids
UASB Upflow anaerobic sludge blanket
WHO World Health Organization

Nomenclature

B	Boron
BO_3	Borate
Ca	Calcium
$CaCO_3$	Calcium carbonate
Cd	Cadmium
Cl	Chloride
Co	Cobalt
CO_2	Carbon dioxide
Cr	Chromium
Cu	Copper
Fe	Iron
HCO_3^-	Bicarbonate ion
Hg	Mercury
K	Potassium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
Na	Sodium
Na^+	Sodium ion
NaOH	Sodium hydroxide
NH_3	Ammonia
NH_4^+	Ammonium
Ni	Nickel
NO_2^-	Nitrite
NO_3^-	Nitrate
P	Phosphorus
P_2O_5	Phosphorus pentoxide
Pb	Lead
PO_4/PO_4-P	Phosphate
PO_4^{3-}	Phosphate ion
S	Sulphur
SO_4^{2-}	Sulfate ion
Zn	Zinc

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