Challenges and opportunities for citrus wastewater management and valorisation: a review

[1]Caterina Lucia, [1]Vito Armando Laudicina*, [1]Luigi Badalucco, [1]Antonino Galati, [1]Eristanna Palazzolo, [2]Michele Torregrossa, [2]Gaspare Viviani, [2]Santo Fabio Corsino

[1]Department of Agriculture, Food and Forest Sciences, University of Palermo, Viale delle Scienze, building 4, 90128 Palermo (Italy);

[2]Department of Engineering, University of Palermo, Viale delle Scienze, building 8, 90128 Palermo (Italy);

*Corresponding author: Vito Armando Laudicina; Department of Agriculture, Food and Forest Sciences, University of Palermo, Viale delle Scienze, building 4, 90128 Palermo (Italy);
email vitoarmando.laudicina@unipa.it; tel. +3909123897074

doi.org/10.1016/j.jenvman.2022.115924

ABSTRACT

Citrus wastewaters (CWWs) are by-products of the citrus fruit transformation process. Currently, more than 700 million of m³ of CWWs per year are produced worldwide. Until nowadays, the management of CWWs is based on a take-make-use-dispose model. Indeed, after being produced within a citrus processing industry, CWWs are subjected to treatment and then discharged into the environment. Now, the European Union is pushing towards a take-make-use-reuse management model, which suggests to provide for the minimization of residual pollutants simultaneously with their exploitation through a biorefinery concept. Indeed, the recovery of energy nutrients and other value-added products held by CWWs may promote environmental sustainability and close the nutrient cycles in line with the circular bio-economy perspective. Unfortunately, knowledge about the benefits and disadvantages of available technologies for the management and valorisation of CWWs are very fragmentary, thus not providing to the scientific community and stakeholders an appropriate approach. Moreover, available studies focus on a specific treatment/valorisation pathway of CWWs and an overall vision is still missing.

This review aims to provide an integrated approach for the sustainable management of CWWs to be proposed to company managers and other stakeholders within the legislative boundaries and in line with the circular bio-economy perspective. To this aim, firstly, a concise analysis of citrus wastewater characteristics and the main current regulations on CWWs are reported and discussed. Then, the main technologies with a general comparison of their pros and cons, and alternative pathways for CWWs utilization are presented and discussed. Finally, a focus was paid to the economic feasibility of the solutions proposed to date relating to the recovery of the CWWs for the production of both value-added compounds and agricultural reuse.

Based on literature analysis an integrated approach for a sustainable CWWs management is proposed. Such an approach suggests that after chemicals recovery by biorefinery, wastewaters should be directly used for crop irrigation if allowed by regulations or addressed to treatment plant.

The latter way should be preferred when CWWs cannot be directly applied to soil due to lack of concomitance between CWWs production and crop needs. In such a way, treated wastewater should be reused after tertiary treatments for crop irrigation, whereas produced sludges should be undergone to dewatering treatment before being reused as organic amendment to improve soil fertility. Finally, this review invite European institutions and each Member State to promote common and specific legislations to overcome the fragmentation of the regulatory framework regarding CWWs reuse.

Keywords

wastewater reuse; intensive wastewater treatment; extensive wastewater treatment; costs and benefits analysis; agricultural reuse; circular economy model

Abbreviations

AGS, aerobic granular sludge
BOD, biochemical oxygen demand
CAS, conventional activated sludge
COD, chemical oxygen demand
CWTs, centralized waste treatment industries
CWWs, citrus wastewaters
EO, essential oil
MBR, membrane bioreactor
OLR, organic loading rate
PHA, polyhydroxyalkanoates
RBCs, rotating biological contactors
SBMBR, sequencing batch membrane bioreactor
TFs, tricking filters
TSS, total suspended solid
UWWTD, Urban Wastewater Treatment Directive
VFAs, volatile fatty acids
WWTP, wastewater treatment plant

1. Introduction

During last decades, the increase of global consumption of natural resources has moved the attention of researchers and stakeholders toward the achievement of a sustainable development concept, which aims to reduce costs on environment, economy and society. In this context, meeting the international regulations and standards, while simultaneously recovering value-added products from waste streams, are becoming increasingly important factors that push forward the implementation of the circular economy model.

In this framework, the agro-food industry has embarked on a path against the waste of raw materials and co-products and is moving from a linear model towards a management approach based on the circular economy paradigm (Mak et al., 2020; Yadav et al., 2022). Agro-food wastes have high potential in the form of energy and nutrients recovery (Vaish et al., 2020). This not only would promote the processes sustainability but also facilitate to close environmental nutrient cycles in line with the circular bio-economy perspective (Mak et al., 2020; Vaish et al., 2020).

The citrus industry plays an important role in the agro-food industrial sector. Citrus fruits are among the most widespread crops in the world (Schimmenti et al., 2013). They are grown over an area of 11.4 million ha. According to the Statistical Bulletin of Food and Agriculture Organization (FAO), global citrus fruits production from 2011 to 2019 increased by 12% thus reaching a production of nearly 144 million Mg (FAO, 2020). The five most important citrus-producing countries in 2019 were China, Brazil, India, Mexico and Spain. On average, more than 20% of the total production of citrus fruits is addressed to industrial processing, primarily oriented to juice production and essential oils (EO) extraction (Zema et al., 2019). From the citrus fruits transformation processes two by-products are obtained: a solid/semisolid fraction, constituted by peels and fruit residues, and the citrus wastewaters (CWWs).

In the literature, there are several reviews that addressed solutions for the valorisation of the solid/semisolid fraction. These studies indicated that the solid fraction of citrus fruit is generally addressed for disposal or reused as source of relevant bioactive compounds showing a wide range of health effects, thus making it exploitable by pharmaceutical, cosmetic, and food industries (Nieto et al., 2021). Moreover, it might also be directed to dietary fibres (Zema et al., 2019) and fertilizers production, essential oils, phytochemicals and pectin extraction, as well as applied as absorbent material (Calabrò et al., 2016). However, this fraction, being rich in organic matter, could represent a serious environmental issue due to its potential putrescence, i.e. hard to dispose as waste (Tripodo et al., 2004).

CWWs are a mixture of fruit constitution water and process water. They are mainly derived from fruit washing, plants, and device cleaning, as well as cooling, essential oil extraction, and peel drying (Zema et al., 2019). Indeed, they may also include effluents derived from the production of citric acid and pectin, citrus molasses, and peel oil depending on treatment plant type(Sharma et al., 2017). CWWs are characterized by low pH and high electrical conductivity. Moreover, they are rich in organic matter and contain nitrogen, phosphorus, some microelements (B, Al, Fe, Zn, Cu) and traces of essential oils. However, due to the different processes contributing to their formation, the chemical properties of CWWs may be extremely variable, even daily. Until nowadays, the management of CWWs is based on a take-make-use-dispose model. Indeed, after being produced within the citrus processing industry, CWWs are subjected to treatment and then discharged into the environment. Previous studies have estimated that the amount of CWWs accounts for approximately 1 to 17 m^3 per ton of processed fruits (Calabrò et al., 2018; Di Trapani et al., 2019) depending on the plant's technology for fruit processing. Apart from the large volume to be handled, the management of CWWs represent serious constrains from both an environmental and economic point of view, because of the intrinsic characteristics of such wastewater. Indeed, the low pH (<4.5) (Tamburino et al., 2007), high concentration of organic matter (Corsino et al., 2021a) and essential oils (Calabrò et al., 2016), could produce significant environmental impact if proper disposal practices are not implemented. Complying with the current environmental regulations, which are increasingly stringent, implies the application of novel intensive treatments that generate high costs weighing on the industries budget. On the other hand, simplified treatment systems are admitted only in developing countries, due to the different environmental regulations and socio-economic conditions (Zema et al., 2019).

Most of the literature studies concerning the CWWs management mainly focuses on the optimization of the treatments aimed at minimizing the environmental impacts of CWWs disposal. However, the global environmental policies on wastewaters are pushing forward not only to minimize their residual pollution concentrations, but also their exploitation by a biorefinery approach and reuse. In this sense, there is an urgent need to move towards wastewater reuse, as demonstrated by the recent publication of the new regulation (Regulation UE 2020/741) which aims to promote the reuse of both municipal and industrial wastewaters especially in the food sector (Shrivastava et al., 2022). Indeed, food sector plays a significant role in the transition from fossil-based linear economy to sustainable circular bio-economy (Mak et al., 2020). As empathized in a recent study, a strategic approach for wastewater reuse is not only to avoid unnecessary use of higher quality water and encourage the reuse of treated water, but also to encompass the possibilities to recover various value-added resources from wastewater (Shrivastava et al., 2022). Among these, the same wastewater (treated or not), could be used for agricultural purposes, since this requires more than 50% of the total fresh water for human consumption (Mateus et al., 2021). Bearing in mind this, several solutions for a sustainable treatment and valorisation of CWWs have been reported in the literature. Recent studies have demonstrated that, by adopting innovative technologies, CWWs can be used for the extraction of value added compounds and recovery of chemicals (Zema et al., 2019), or just treated while minimizing the impact deriving from their release into the environment (Corsino et al., 2021a; Martín et al., 2010). Indeed, CWWs were successfully exploited for the recovery of polyhydroxyalkanoates (PHA) (Corsino et al., 2022), or agricultural reuse (Ioppolo et al., 2020). However, knowledges about the benefits and disadvantages of these technologies are very fragmentary, thus they are not thoroughly known by the scientific community and stakeholders. Moreover, available studies focus on a specific treatment/valorization pathway of CWWs and an overall vision, who’s prospective should be toward an integrated approach for a sustainable CWWs management, is still missing. Indeed, the integration of these conversion processes leads to sub-products, which provides an extra benefit in product recovery and overcomes the restrictions of individual stage (Mak et al., 2020). In addition, considering the recent developments of regulations on wastewater reclamation and the need of the citrus industrial sectors to move towards this direction, a focus on the opportunities and perspectives referring CWWs reuse is required.

To fill this gap is important to understand at what stage the research on CWWs is and what are the potential future lines of research to be undertaken for their proper disposal or reuse with a special view to an integrated approach among all these technologies.

In light of this, this review aims to provide an integrated approach for the sustainable management of CWWs to be proposed to company managers and other stakeholders within the legislative boundaries and in line with the circular bio-economy perspective. To this aim, firstly, the main current regulations on CWWs disposal and reuse, and a concise analysis of citrus wastewater characteristics are reported and discussed. Then, the main technologies that have been implemented over the previous decades for CWWs treatment are reported with a general comparison of their pros and cons, and focusing on the main concerns related to a sustainable management as well as the opportunities to recover, wherever possible, valuable resources. In addition, alternative pathways for CWWs utilization, such as that for crop irrigation, are presented and discussed. Finally, a focus was paid to the economic feasibility of the solutions proposed to date relating to the recovery of the CWWs for the production of both value-added compounds and agricultural reuse.

2. Legislative aspects

Citrus industries employ large quantities of water for fruits processing. These operations produce effluents that need proper treatments before their disposal because of the high content of organic matter and other compounds (i.e. surfactants, essential oils, etc.), but also due to low pH and high degree of corrosiveness (Suri et al., 2020). Such properties might cause several environmental impacts if CWWs were improperly disposed, including water and groundwater pollution, toxicity for aquatic organisms, proliferation of vectors for diseases, as well as greenhouse gases emissions during their degradation in soil. For the above reasons, CWWs are subject to strict regulations for their disposal. However, nowadays CWWs are usually directly released into water bodies, treated in intensive or extensive treatment plant, or discharged into the public sewer after proper treatments (Zema et al., 2019), which means that the disposal strategies not always depend on local environmental regulations but sometimes more on specific conditions. In general, water use and wastewater disposal are regulated by national and regional legislations transposed by EU laws. The main EU laws on the environment protection that concern industrial wastewater treatment and reuse are the following: Directive 91/271/EEC (Directive 91/271/EEC, 1991) and Regulation (EU) 2020/741 (Regulation EU 2020/741, 2020).

The Directive 91/271/EEC (Urban Waste Water Treatment Directive - UWWTD) concerns the urban wastewater collection, processing, and discharge, as well as treatment and discharge of wastewater originating from certain industrial sectors. It aims to protect the environment from possible risks associated to wastewaters. This regulation claims that "*discharges from certain industrial sectors of biodegradable industrial wastewater…should be subject to appropriate requirements*" and "*should be subjected to special authorization*". These industrial sectors are listed in the Annex III, in which CWWs can be enumerated in the "*Manufacture of fruit and vegetable products*". The Directive 91/271/EEC also defines the minimal requirements and treatment levels necessary for these wastewaters. More specifically, *"…the discharge of industrial wastewater into collecting systems and urban wastewater treatment plants is subject to prior regulations and/or specific authorizations by the competent authority or appropriate body*" (article 11), and "*…industrial wastewater entering collecting systems and urban wastewater treatment plants shall be subject to such pre-treatment*" (Annex I). Therefore, specific requirements in the regulations/authorizations for CWWs discharges into urban wastewater systems are defined under article 11 and Annex IC. The same directive deals with direct discharges under Art. 13 from biodegradable industrial wastewater (Annex III). More precisely, Article 11 of the UWWTD requires Member States to ensure that competent authorities regulate and give prior authorization for the discharge of industrial wastewater into collecting systems and wastewater treatment plants (WWTPs). Such authorizations must ensure that industrial wastewater entering the collecting systems and/or the treatment plants is pre-treated, when necessary, so that the functioning of the plant and the collecting system is not hindered and, thus, that discharges from the plants do not adversely affect the environment. However, the requirements of Article 11 are relatively general and the specific interpretation of how to meet the requirements of this article are defined separately by each Member State. The UWWTD also aims to control the sludge generated in the treatment operations, and to ensure that it can be safely disposed of and, if possible, used in certain applications (e.g. agriculture). This implies that citrus processing industries should be equipped with a wastewater treatment plant aimed at reducing the pollutants load of the processing effluents to comply the requirements imposed by regulation. However, specific limit values for industrial wastewater are not indicated in the EU Directive, hence they are demanded to national or regional authorities.

Since in many countries water is becoming an increasingly rare and precious commodity, a more careful and correct management of this resource is needed for industrial processing to reduce simultaneously the quantity of effluents produced (Klemes, 2012). In this context, a new regulation (Regulation UE 2020/741) was recently published and will apply as from the coming June 2023. This regulation aims to promote the reuse of wastewater and to guarantee that reclaimed water is safe for agricultural irrigation, thereby ensuring a high level of protection of the environment and of human and animal health, thus promoting the circular economy, supporting adaptation to climate change. However, this Regulation *"...should not concern biodegradable industrial wastewater from plants belonging to the industrial sectors listed in Annex III to Directive 91/271/EEC, unless the wastewater from those plants enters a collecting system and is subject to treatment in an urban* *wastewater treatment plant*". This likely means that industrial wastewater reuse shall be still delegated to local regulations. Generally, these define the intended and the eligible uses for wastewater reuse, including agricultural reuse for irrigation of crops (human and animal consumption) and irrigation of green areas, civil reuse (for washing streets, powering heating or cooling systems, supply of dual supply networks, with the exclusion of the direct use, etc.) and industrial reuse (fire-fighting, process, washing water, etc.). The reclaimed water quality is divided into four classes, for each of which the permitted uses and irrigation methods are set out. Therefore, a crop belonging to a specific category shall be irrigated with reclaimed water of the corresponding minimum reclaimed water quality class, unless additional requirements (article 5) are requested. This results in achieving the quality requirements foreseen in Table 2, which reports the limits for some quality parameters, like *E. coli*, biochemical oxygen demand, total suspended solid (TSS), turbidity, according to the specific water quality class. The quality requirements for wastewater reuse are very stringent. Indeed, one of the crucial issues in the reuse of treated wastewater for crop irrigation is the residual presence of pathogenic microorganisms which represent a potential health risk to consumers when entering in the food chain (Libutti et al., 2018). Regarding microbiological contamination levels, the corresponding guidelines allow unrestricted crop irrigation with a bacteriological effluent quality characterized by less than 10 CFU 100 ml^{-1} of *E. coli* in 80% of samples. To comply these levels, advanced treatment units (such as filtration, membranes, activated carbon systems, disinfection) are necessary. This entails that wastewater reuse basically depends on the economic viability of the regeneration versus the purchase, use, treatment and discharge of fresh water (Zema et al., 2019).

3. Characteristics of CWWs

The production of CWWs is characterized by a large quantitative and qualitative variability depending on many factors, such as water consumption per weight unit of processed fruits, amount of citrus processed and overall water management in the plant. This variability can, in turn, change annually because of agricultural production, market trends and plant operations.

The yearly total volume of CWWs is affected by the amount of citrus fruits produced during the growing season, which shows both inter- and intra-annual variability (Zema et al., 2019). In the Mediterranean areas, more than 70% of citrus fruit is processed during the trimester February-April, with highest peaks usually set on March (Figure 1) due to the wide production of citrus fruits (Corsino et al., 2018; Zema et al., 2019). The quantitative variability of CWWs changes also weekly and daily because of the plant downtimes during night and weekend. Recently, Zema et al. (2019) estimated a yearly production of more than 700 million of m^3 of CWWs from 2017 due to the increase of citrus fruit intended for the industry. Corsino et al. (2018) reported for an Italian citrus factory processing 25 tons h^{-1} of citrus fruits (lemons, oranges and tangerines), a production of about 17 m^3 of CWWs per tons of processed fruits. Rosas-Mendoza et al. (2018) have estimated in the northern part of the State of Veracruz (Mexico, USA) a production of CWWs in the range from 0.79 to 1.25 m^3 for each tons of oranges processed. However, more data collected (Rosas-Mendoza et al., 2018) have shown values of 1.58–3 m^3 of CWWs produced for each tons of fruit processed. This wide range of water consumption in citrus industries depends on several factors mainly related to the technologies for fruit processing implemented in the factory, the number of processing lines operating simultaneously, processing technologies (e.g., juice, EO, or pulp extraction) and type of fruit (Bozzano et al., 2021). In general, recirculation of water for specific operations (e.g., cooling, EO extraction, etc.) allows saving large volume of fresh water, thus minimizing that of CWWs production. For instance, the cooling towers with open-cycle system requires large quantity of freshwater, thus generating significant volume of CWWs. In contrast, water-cooling closed system allow to significantly reduce wastewater production (Zema et al., 2018).

Concerning the qualitative variability, it depends not only on the type and stage of fruit ripeness but on the technological and construction characteristics of the transformation plant too. The main parameters measured for CWWs characterization are (Table 1) pH, biochemical and chemical oxygen demand (BOD and COD, respectively), total nitrogen (TN), total phosphorus (TP), TSS, soluble potassium (K), magnesium (Mg) and calcium (Ca), essential oils (EOs) (Corsino et al., 2018; Koppar and Pullammanappallil, 2013a). Generally, washing, and cooling operations produce wastewater with a low pollutants load, whereas other processing units (e.g., EO, fruit extraction) generate a significant increase in the organic pollutant's concentration. Cleaning and cooling operations (e.g., machineries and equipment's) produce a dilution effect referring to some parameters (BOD, COD, EO) while increasing, in some cases, the concentration of others (surfactants, pH, TP, etc.) depending on the type of chemicals used. Values of COD and TSS are very variable depending on the various stages of the transformation processes (Corsino et al., 2022). Data available in the literature referring to COD concentration indicate a wide range of variation between approximately 5000-75000 mg L^{-1}. This could depend on the sampling point, since CWWs generated from juice and EO extraction, or peel dehydration are characterized by very high organic matter concentration (>60-70 g L^{-1}) (Garcia et al., 2019), but also on the plant process design. In general, recirculation of water in fruit processing units generate CWWs with higher pollutants concentration, whereas water open-cycle systems determine a significant dilution. Minor variations could be due to the type of fruit processed.

CWWs have acid reaction due to the high content of acidic compounds among which the most abundant are citric and malic acids (Sharma et al., 2017). Variations in pH of CWWs could be partly attributable to the type of fruit (Zema et al., 2019), but more in general to the use of alkaline chemicals for cleaning operations. Based on the operating volume of the equalization unit, wastewater generated from cleaning operations could buffer the pH of CWWs. Similarly, the amount of TN and TP are very variable, although their concentrations in relation to that of COD are very low (C/N >1000). It is worth to observe that CWWs are characterized by the presence of other trace element in not negligible concentrations. The presence of such elements makes CWWs interesting for agricultural purposes to improve soil fertility (Ioppolo et al., 2020).

4. Potential use and reuse of CWWs

Citrus fruit wastes consist of solid/semisolid fraction and CWWs. The latter can be i) exploited for the recovery of chemicals trough biorefinery (Fazzino et al., 2021; Sharma et al., 2017), ii) addressed to lagooning (Zema et al., 2019), iii) addressed to wastewater treatment plant (Corsino et al., 2018; Martín et al., 2010), or iv) reused in agriculture for crop irrigation (Ioppolo et al., 2020) (Figure 2). Techniques and methods for the recovery of chemicals are well established, studies about aerobic and anaerobic CWWs treatment are still in progress, whereas those about lagooning and their reuse in agriculture are still at the beginning. Chemicals recovered from CWWs are phenolic acids, flavonoids, carotenoids, limonoids and essential oils. Such chemicals are extracted from CWWs by using solvents with different polarity, followed by precipitation or centrifugation (Sharma et al., 2017).

4.1 CWWs storage

The variability of the raw CWWs characteristics could represent a critical issue for the WWTP since they would operate under variable conditions that might result in poor purification performances especially during the load peaks and transaction periods (start-up and end of citrus season). The reason for this is that some processes (e.g., biologic units, secondary clarifiers) might not allow excessive hydraulic or organic loads. Therefore, WWTPs serving citrus processing industries should be equipped with proportioning and equalization units to limit and minimize the effects of load variations. Equalization is a method of retaining wastewater in a basin so that the effluent discharged is fairly uniform in its quality characteristics, whereas proportioning means the discharge of CWW in proportion to the flow treatment capacity of the WWTP (Nemerow, 2007). In most of cases, it is possible to combine equalization and proportioning in the same basin. A secondary but significant effect is that of lowering the concentration of effluent pollutants, especially if during cyclic productions of citrus industries large quantity of fresh water is used (e.g., floor and equipment washing). In addition, as pH varies along the day, since usually alkaline chemicals are used at the end of the production cycle, an efficient equalization unit could considerably reduce the needs of chemicals used for pH neutralization. Indeed, CWWs produced during the fruit processing phases are characterized by low pH (3-4.5), whereas once the fruit processing has finished the cleaning operations produce wastewater characterized by very high pH (>11). Thus, the buffering capacity of the latter wastewater could result in a substantial cost saving for chemicals supply.

Nonetheless, storage of not treated CWWs is necessary also when the purpose is their direct reuse for crop irrigation. Indeed, the production of CWWs may span a long period, from days to months, and not totally coincide with crop water needs. The storage of CWWs requires the existence of facilities and suitable places (Bonari et al., 2007). During the storage, CWWs may undergo to fermentation process due to the high content of carbohydrates and scarcity of oxygen. Fermentation led to the production of gases such as bio-hydrogen (Zema et al., 2019) and methane (Calabrò et al., 2016), and also volatile fatty acids as result of hydrolysis, acidogenesis and acetogenesis processes (Corsino et al., 2021a). To prevent the occurrence of biological activities in the storage units, fermentation inhibitors could be used. Efficient inhibitors may be furfural, 5-hydroxymethylfurfural, acetic, lactic or formic acids (Narendranath et al., 2001). However, if fermentation inhibitors are used, the quality of CWWs has to be evaluated before their further uses.

4.2 Intensive CWW treatments

According to EU regulations (Directive 91/271/EEC, 1991) industrial wastewaters could be discharged into urban collecting systems after appropriate preliminary treatments. The most developed techniques for industrial wastewaters purification are intensive treatments carried out in WWTP located within the production site. The principle with these processes is to intensify the phenomena of the transformation and dissimilation of organic matter as occur naturally, thereby allowing to operate on a reduced surface area (Guo et al., 2016). Intensive treatments could be performed in different ways by means of several technologies. The most used intensive technology in WWTPs for CWWs treatment is the conventional activated sludge (CAS) process, although other intensive technologies such as rotating biological contactors (RBCs) or tricking filters (TFs) are available (Matamoros et al., 2016). In some cases, especially for small potential WWTPs, extended aeration system, which is a modification of the CAS process with a higher sludge retention time, is adopted. More rarely, advanced treatments are applied (i.e., MBR, membrane bioreactor) and only for special requirements (i.e., wastewater reuse, small space availability, etc.). Intensive biological treatments are characterized by several drawbacks mainly linked to the variability of CWWs characteristics and the presence of toxic compounds (e.g., EO), the long-start up times necessary to achieve steady-state conditions when the plant is reactivated after the not operating period (summer), and the high energy requirements (> 2 kWh $kgCOD^{-1}$). More details about the applications and comparison of the main biological processes are provided in the following sections. Alternative treatment systems to biologic processes are based on physical and/or chemical (i.e., clarification-flocculation, concentration by evaporation, advanced oxidation processes). These are of limited use for CWWs, since these plants are expensive and have higher energy requirements than biologic based processes (Zema et al., 2019). Therefore, biological processes are still the most used for CWWs treatment.

Another possibility for CWWs handling is the disposal in centralized waste treatment industries (CWTs). The CWTs handle both wastewater treatment residuals and industrial process by-products that come from several industries. CWT facilities receive a wide variety of hazardous and non-hazardous industrial wastes for treatment. CWWs treatment with other effluents could be a viable option to reduce the drawbacks related to their treatment in a dedicated WWTP. Indeed, by blending CWWs with municipal and/or other industrial wastewater it could be possible to reduce the concentration of toxic compounds, overcome the issue related to the seasonal variability and exploit synergistic effects deriving from the co-treatment with other effluents (e.g, blending with wastewater with low C/N ratio).

CWWs treatment at a WWTP located within the production site implies both high capital costs for all the facilities construction (200-700 € PE^{-1}), as well as operating ones for all the management activities necessary for CWW treatment (2.0 kWh kg $COD_{removed}^{-1}$). In contrast, treatment of CWWs in CWTs entails high disposal (100-300 € m^{-3}) and transportation costs, whose incidence on the overall industry economy depends on the distance from the disposal site. Consequently, the choice between these two alternatives is based mainly on economic criteria.

All these treatment processes involve several challenges, including high-energy consumption, financial costs and environmental impact, as well as a need to be resilient to a periodic variability of the wastewater characteristics. Alternative management/treatment approaches for some of the above processes could help to meet these challenges by reducing the economic and environmental burden as well as turning wastewater into valuable resource. Accordingly, the traditional approach whereby wastewater must be purified sufficiently to meet the environmental regulations, is going to be moved to the concept of biorefinery, in which waste streams are used as a valuable substrate with concomitant water treatment. The implementation of the biorefinery concept could change the open-model of industrial activity towards a more virtuous path in which those components of wastewaters, which have value, could be reused. The biorefinery concept is a driving force towards the implementation of cleaner production in the industrial sector.

In the following sections, a comprehensive review of the main technological solutions for CWWs treatment and valorization is provided in view of a sustainable, synergic and integrated approach consistently with the biorefinery and circular economy models.

4.2.1 CWWs anaerobic treatment

Anaerobic treatment is one of the most common methods for agro-food wastes management (Sharma et al., 2017). In fact, this process makes possible the simultaneous removal of the organic pollution, the reduction of waste streams to be disposed and the production of high-value added by-products (Rosas-Mendoza et al., 2020). The biorefinery approach involving CWWs might have a high potential impact on the development of circular economy in the citrus-processing sector. Because of the high organic matter content, CWWs have an attractive bioenergy and bio-products potential. Indeed, several studies have focused on volatile fatty acids, hydrogen, and methane production from CWWs, through the combination of dark fermentation and anaerobic digestion processes (Lukitawesa et al., 2018; Torquato et al., 2017). However, due to the presence of inhibiting compounds, such as essential oils (D-limonene), the application of anaerobic treatments aimed at the valorisation of CWWs for energy purposes is challenging (Calabrò et al., 2020; Zema et al., 2019). Therefore, specific pre-treatments, such as hydrothermal treatment (Saadatinavaz et al., 2021), or dilution with other liquid streams, like fruits and machineries cleaning waters (Corsino et al., 2021a), are generally performed before anaerobic treatment to decrease the concentration of such inhibiting compounds. Alternatively, given the high-market value of such products, an integrated biorefinery approach could be advisable to recover essential oils before performing anaerobic treatments. Indeed, EO has promising potential application in several sectors from the food industry (for production of pectin, dietary fibres, etc.), to the cosmetic and pharmaceutic Industries (extraction of flavonoids, flavouring agents and citric acid) (Zema et al., 2018). However, in many cases, these uses are still not economically sustainable. Several studies have focused on the development of new separation techniques for the chemical, food and pharmaceutical industries and lately received a lot of attention due to the increasing energy prices and the drive to reduce CO_2 emissions. In this sense, a process based on microwave hydro-diffusion permits fast and efficient extraction, reduces waste, avoids water and solvent consumption, and allows substantial energy savings (Bousbia et al., 2009).

Anaerobic digestion is defined as the biological conversion under reducing conditions of organic matter into a variety of products, including biogas. Biogas is a mixture of gases mainly composed by CH_4 (40–65%) and CO_2 (35–60%) along with other minor components (H_2O, H_2S, NH_3) (Rosas-Mendoza et al., 2018). Among these, methane is the most attractive compound within biogas since its potential use for renewable energy. Nevertheless, an accurate control of the main operating parameters is necessary during the digestion process, as a function of the composition of CWWs and the aims of the process. A down-flow stationary fixed film anaerobic digester was successfully operated for 76 days under thermophilic (55°C) conditions. At an average organic loading rate (OLR) of 0.51 kg COD/m^3 d^{-1} and a hydraulic retention time of 16 days, the reactor yielded 2.1 Nm^3 of biogas per m^3 of treated wastewater. No long term toxicity issues due to limonene were observed (Koppar and Pullammanappallil, 2013a). A recent study tested a high-rate anaerobic hybrid reactor to perform the anaerobic digestion of effluents from a citrus industry (Rosas-Mendoza et al., 2018). The reactor obtained high soluble and total COD removal (85%), as well as high methane yields close to 0.15 L CH_4 g $COD_{removed}^{-1}$, operating at an OLR of 8 g COD L^{-1}d^{-1}. Nevertheless, the authors observed an inhibitory effect on methanogenic bacteria due to the presence of D-limonene since no pre-treatment was performed for elimination of this essential oil. This caused a decrease in the COD removal and methane yields, especially when the reactor was operated at high OLR. However, the authors stressed that the configuration of the reactor allows handling high organic loads, and, due to the presence of the biofilm, the inhibitory effect of D-limonene can be minimized.

To minimize the effect of D-limonene on methane production, a two-stage anaerobic digestion with internal recirculation was proposed (Lukitawesa et al., 2018). The effluent from the first stage was filtered to separate and discharge the solid phase rich in D-limonene from the liquid one containing less D-limonene, that was fed in the second stage. A higher methane yield (160–203 NmL gVS^{-1}, where VS are volatile solids) was observed compared with a control reactor without the solid-phase separation (60–133 NmL gVS^{-1}). The effect of D-limonene removal through hydrothermal process was recently investigated (Saadatinavaz et al., 2021). The bio-methane produced from the untreated orange waste (OW) residue was 194 NmL gVS^{-1}, higher than that from the pre-treated residues. The reason might be the removal of hemicellulosic sugars and other biodegradable materials when the organic waste was subjected to pre-treatment and enzymatic hydrolysis. In another study, the removal of D-limonene through a solvent-extraction method produced a significant increase of the methane yield (Battista et al., 2020). The authors demonstrated that the methane potential of extracted and unextracted orange peels was comparable (355–365 NL CH_4 kgVS^{-1}), although the orange peels without a previous limonene extraction took twice as long to reach the final methane production. All the studies seem to confirm that removal of essential oils prior to anaerobic digestion is crucial for maximize bio-methane productivity and kinetics. Nevertheless, these treatments should not involve other compounds, especially biodegradable materials. Improvement of process kinetics is of a matter of importance especially in order to reduce the plants footprint. Higher process kinetic would require smaller reactors or the possibility of increasing the treatment capacity of existing ones.

Volatile fatty acids (VFAs) are one of the largely used compounds in the chemical industry that serve as starting materials for biofuel production and for the synthesis of a variety of products, such as biopolymers, reduced chemicals, and derivatives (Strazzera et al., 2018). VFAs have a wider range of applications, from the food, pharmaceutical, and cosmetics industries to biofuels (e.g., biobutanol) and bioplastics (polyhydroxyalkanoates) production (Hunter et al., 2021).

VFA production from CWWs was studied in MBR operating at OLR up to 8 g VS L^{-1}d^{-1} (Lukitawesa et al., 2021). VFAs were mainly constituted by acetate, whereas the fraction of butyrate, caproate, and propionate was lower. Without performing any pre-treatment, the highest yield of VFAs, 0.67 gVFA g VS^{-1}, was achieved at OLR 4 g VS L^{-1}d^{-1}. Contrarily, when CWW was pre-treated to remove D-limonene, the VFA yield increased to VFAs 0.84 gVFA gVS^{-1} operating at the same OLR. At higher OLR (8 g VS L^{-1}d^{-1}) the authors observed a sharp decrease in yield only for the untreated CWW. Moreover, Corsino and co-authors evaluated the effect of operating conditions on VFA production from CWW subjected to dilution with other processing effluents (Corsino et al., 2021a). The authors found that acetate production was maximized by operating under unbalanced nutrients (C: N: P = 200:0.1:0.1), without removing the particulate fraction and operating at pH higher than 5. The authors stressed that dilution with other processing streams enabled to minimize the effects of the essential oils on process yield and kinetics. Similarly, in another study it was observed the VFA production from orange peel fermentation after limonene recovery was close to 0.35 g VFA gTS^{-1} after 5 days only (Battista et al., 2020), where TS are total solids. Among the other by-products achievable from anaerobic treatments, the hydrogen (H_2) may be a valuable resource to be used for local energy supply, reducing the operational costs of citrus industries facilities. The bioconversion of CWWs to hydrogen through dark fermentation was recently reported in the literature (Torquato et al., 2017). The authors demonstrated that CWWs showed significantly higher potential for H_2 production when compared to synthetic and domestic wastewaters, resulting in a H_2 bioconversion efficiency close to 73%. In another study, the hydrogen production from CWWs was maximized by applying an electroporation treatment at different intensity levels (30-120 kWh m^{-3}) to achieve methanogen inactivation (Karim et al., 2019). In comparison with other pre-treatments, the highest hydrogen production of 896 mL was achieved with the electroporation treatment, followed by sonication with a probe (678 mL), sonication in a bath (563 mL) and heat-shock treatment (545 mL).

Overall, anaerobic treatments could be considered a preliminary stage for CWWs since the residual organic pollution is not suitable for their release into the environment. Thus, additional downstream treatments are required to meet the standards imposed by the environmental regulations.

Nonetheless, it is worth to stress that anaerobic treatment of high-strength wastewater allows not only to reduce the overall energy requirement necessary to comply the environmental regulations but additionally it provides synergistic effects deriving from the integration with other treatments (e.g., biologic aerobic processes). For instance, volatile fatty acids represents the ideal substrate for the enrichment of mixed microbial culture with microorganisms able to produce PHA in aerobic downstream systems (Argiz et al., 2020).

4.2.2 CWWs aerobic treatment

Aerobic biological treatments are generally considered as an alternative to the anaerobic ones for CWWs treatment.

Aerobic biological treatments are generally based on conventional activated sludge (CAS) systems or on biofilm processes (i.e. trickling filters). Although these processes are widely applied for the treatment of municipal wastewater, their replication for CWWs treatment is challenging (Zema et al., 2019). Indeed, specific characteristics of CWWs makes conventional processes unsuitable to meet the discharge limits imposed by European regulations (Directive 91/271/EEC, 1991). The main drawbacks of aerobic processes referring to CWWs treatment are related to the high organic matter content, nutrients imbalance, seasonal and weekly flow rate variability, high energy requirements especially for aeration system, etc. (Di Trapani et al., 2019). Moreover, some specific characteristics of CWWs, such as the high availability of readily biodegradable organic matter, low pH and imbalance of carbon/nitrogen ratio are favourable for the occurrence of dysfunction in the CAS process (Jenkins et al., 2003). Filamentous and viscous bulking, as well as biological foaming are high risk factors for a CAS based treatment of CWWs. These dysfunctions could occur simultaneously and could create severe issues in the solid-liquid separation phase (Corsino et al., 2018).

Nutrient imbalance could be easily addressed by adding nitrogen (N) and phosphorous (P) to achieve a COD:N:P ratio close to 200:5:1 (Metcalf and Eddy, 2015). This could prevent the occurrence of viscous bulking (Wanner, 2017). Filamentous bulking and biological foaming are more difficult to be addressed since many of the trigger factors are peculiarities of CWWs. In such cases, application of metabolic selection methods (i.e. anoxic or anaerobic selectors) could prevent the overgrowth of specific filamentous organisms (i.e. Nocardia Amarae-Like Organisms, NALO). Seasonal and daily variability is a considerable drawback for biological based processes. Indeed, it could cause significant load variations, occurrence of process dysfunctions, affect the microbial community structure and consequently the treatment's efficiency. A well-designed storage and equalization unit is necessary to prevent load-shock during daily and weekly flow fluctuation. Large equalization basins could reduce the CWWs variability and limit the instability and breakdown of the processes. This could also be helpful to exploit the buffering capacity of some liquid streams deriving from routinely operation within the production process (i.e. a storage tank washing with sodium hydroxide), thereby reducing the amount of chemicals necessary for pH neutralization before the biological treatment (Hawash et al., 1988). Nevertheless, because of the high space requirement, their integration within the production site is not always feasible. In addition, seasonal variation of CWWs quantities produces drawbacks during two transit times corresponding to the increase or decrease of CWWs production: i) during the plant start-up (winter period) and ii) at the end of citrus season. In the first cases, the sudden increase of the food to microorganism ratio could cause the onset of dispersed growth (Wanner, 2017), since the high availability of organic substrate decrease the production of extracellular polymeric substances by bacteria, reducing the activated flocs size. On the other hand, in the second case, the long starvation period (low F/M and long sludge retention time) could cause the onset of pinpoint floc, which consists of the formation of small flocs (< 50 μm) with poor settling properties. The long-term loading changes caused larger disturbances to the floc size distribution than more rapid but shorter ones (Barbusiński and Kościelniak, 1995). Generally, after the substrate overload occurred, the flocs are more prone to breakup, thus increasing the effluent turbidity. In such cases, the addition of flocculating agent could be a temporary solution to mitigate the problem. A modular WWTP constituting by different biologic reactors operating in parallel could be a practical solution to have a flexible system able to be adapted to load variations. In addition, depending on the storage capacity available and on the plant design, CWWs with high organic content (e.g., peel drying or EO extraction) could be stored during the winter and gradually treated in the WWTP during the summertime. Moreover, it could be suggested to reduce the aeration rate or switching off on briefly times a day to reduce bacterial endogenous respiration and limit sludge stabilization. Certainly, this practice loss its effectiveness as the standstill time increases (Edwards and Norman, 2015). Other techniques, such as the addition of enzymatic products or activated sludge from other plants, could be used to speed up the start-up phase, although these are very expensive and of limited applicability (Folino et al., 2018).

The high-energy requirements for aerobic treatment of CWWs still remain a serious drawback. The energy requirement of these plants can be close to 2.0 kWh kg COD^{-1} (0.86 $kgCO_2$ $kgCOD^{-1}$), that is about four times greater than that required for municipal wastewater treatment (Zema et al., 2019), mainly due to the high concentration of readily biodegradable organic matter in soluble form. The integration of anaerobic with aerobic treatments in a synergistic way could help to minimize the overall impact of intensive treatments, while maximizing the energy and material recovery from CWWs treatment. In this sense, the integration with anaerobic upstream treatment could noticeably reduce the energy requirement for aeration since the most of organic matter is removed without oxygen requirement and more it allows recovering energy through biogas production. Indeed, anaerobic treatment could reduce the organic content of CWWs for the downstream aerobic process, while producing biogas suitable for energetic purposes (e.g., heat or electric energy production) and effluent enriched in volatile fatty acids. The effluent from AD could be treated in intensive aerobic processes with a double advantage: i) handling with effluent enriched in VFA could be beneficial to enrich the activated sludge with PHA-storing bacteria, thus offering a further pathway for excess sludge valorization (PHA recovery), and ii) decreasing of the organic content reduces the energy requirements.

Another approach studied to minimize the environmental impact of CWWs aerobic treatment is the implementation of advanced processes. Advanced aerobic technologies such as aerobic granular sludge (AGS) and MBR were successfully adopted for CWWs treatment both in single and sequential stage. Corsino et al. (2018) examined the treatment of CWWs in two AGS reactors operating at OLR ranging between 3.0-15 kg COD $m^{-3}d^{-1}$ and at pH of 7.0 and 5.5. The authors found that high COD removal (> 90%) could be achieved by operating at OLR not higher than 7 kg COD $m^{-3}d^{-1}$ and pH close to neutral conditions, while ensuring an appropriate balance between the feast and famine phases to prevent the overgrowth of fast-growing microorganisms (e.g., filamentous bacteria) and ensure the granules stability in the long term. AGS allows reducing significantly the energy costs for wastewater treatment being close to 0.35 kWh $kgCOD^{-1}$ (0.15 $kgCO_2$ $kgCOD^{-1}$) (Giesen et al., 2013). AGS was also coupled with MBR technology in a in series AGS/MBR configuration (Di Trapani et al., 2019). This scheme was also compared to the conventional MBR one. The results demonstrated that both plant configurations enabled very high COD removal, with average values close to 99%. Nevertheless, higher fouling tendency was observed in the AGS/MBR configuration due to AGS deflocculation. This might severely affect the membrane service life. A recent study evaluated the treatment of CWWs in a sequencing batch membrane bioreactor (SBMBR) with activated sludge enriched in microorganisms able to store intracellular biopolymer such as polyhydroxyalkanoate (PHA) (Corsino-Membranes). The authors demonstrated that the enrichment of the sludge with PHA-storing bacteria was favoured by the characteristics of CWWs (high soluble COD availability, low nitrogen content) that enabled to mitigate the fouling behaviour of the membrane and to achieve high removal performances at high OLR (> 3 kgCOD $m^{-3}d^{-1}$). Among the available studies, MBR allowed obtaining the highest COD removal from CWWs. The specific treatment costs of MBR technology are close to 0.7-1.0 kWh $kgCOD^{-1}$ (0.30-0.43 $kgCO_2$ $kgCOD^{-1}$). However, the lack of knowledge about the use of MBR for CWWs treatment in large-scale application requires additional studies aimed at evaluating the hydraulic performances of the membrane in the long-term, the need of chemicals for fouling maintenance and the overall management costs. Nevertheless, considering the high-quality of the effluent from a MBR, the application of this technology should be advisable only for the purpose of reuse of CWWs. Wastewater reuse within the same industry of for agricultural purposes could significantly contributed to save fresh water supporting a more sustainable use of water resource.

4.2.3 Sludge production

The excess sludge production is another drawback of intensive biological treatments of CWWs. Indeed, the excess sludge generated from the transformation of the organic matter into new biomass entails high expenditure for its treatment and disposal. The handling of excess sludge in municipal wastewater treatment plant is a considerable economic burden, accounting for 30–40% of the total capital cost and 50% of plant operation costs (Valentino et al., 2015). Sludge production from CWWs treatment through aerobic process was estimated about 0.10-0.30 kg VS kg COD^{-1} (Corsino et al., 2018). Considering that the average COD concentration in CWWs is between 5-27 kg COD m^{-3} (Zema et al., 2018), the specific productivity of excess sludge could range between 0.5-9.0 kg SS m^{-3} of treated wastewater. This entails that a considerable amount of excess sludge must be treated and disposed, thereby affecting the overall operating costs related to CWWs treatment. To reduce the impact of sludge treatment on the overall operating costs, innovative solutions aimed at reducing the excess sludge production or valorizing the sludge once produced should be considered (Collivignarelli et al., 2019). The use of efficient sludge dewatering and drying system might considerably decrease the amount of sludge to be disposed. In this context, thermal drying systems of excess sludge allow evaporating significant amount of water in the sludge thereby reducing the final weight to be disposed (Zhu et al., 2022). In the frame of citrus industries, there are several thermal waste streams that could be used as a heat source (e.g. waters from boilers or heaters). This could reduce the need of heat to carry out thermal drying of sludge, thereby minimizing the use of conventional fossil fuels. Considering the high organic content of the sludge produced during CWWs treatment, energy recovery through biogas production in anaerobic digester or agricultural utilization after composting could be a feasible solution in line with the circular bio-economy model. In this sense, sludge could be used as a fertilizer since the organic nitrogen and phosphorous in bio-solids are used quite efficiently by crops upon the mineralization process. Moreover, the supply of organic matter is one of the most important agro-technique to improve structure, minimize erosion, increase water holding capacity and counteract fertility decline of soils of the semiarid Mediterranean environment (Laudicina et al., 2012; Palazzolo et al., 2019).

3.4 Extensive treatment

Extensive treatments of wastewaters have both advantages and disadvantages. Indeed, if on the one hand, these are attractive solutions considering the lower construction costs, energy requirements and reliable purification efficiency, on the other hand, the need of wide areas, the long hydraulic retention time and, possible unpleasant smells due to anaerobic processes are the main constraints related to their use (Carawan et al., 1979; Kimball, 1999). Among the extensive treatments, lagooning is the most widely used (Andiloro et al., 2021; Koppar and Pullammanappallil, 2013a; Lobato et al., 2013). This system is used for the treatment of several types of wastewaters, including agricultural and industrial ones (Kruzic and Liehr, 2008). Indeed, it has proved to be a valid alternative to the treatment of CWWs with positive results (Andiloro et al., 2013).

A lagoon can be defined as a greater or lesser deep basin in which wastewaters are stored. Lagooning refers to a low-cost and efficient treatment process, which requires lower management and mechanical equipment (Andiloro et al., 2021; Zema et al., 2019). It is based on the wastewaters self-purification by aerobic and/or anaerobic microorganisms activity (Andiloro et al., 2021; Lobato et al., 2013).

CWWs can be treated in anaerobic or aerobic biological ponds. The anaerobic treatment is recommended far away from private homes due to the possible production of unpleasant smells and long times and volumes of pond. In order to face issues related to anaerobic treatment, the aerobic one is generally adopted (Indelicato et al., 1997; Kimball, 1999).

However, according to Zema et al. (2019) the best option for CWWs treatment is the use of aerobic-anaerobic aerated lagoon systems, which allow higher purification efficiency and lower energy demand (0.57 kWh $kgCOD^{-1}$ – 0.24 $kgCO_2$ $kgCOD^{-1}$) when the following measures are adopted: i) high depth of pond, ii) optimization of operating hours according to the oxygen demand, and iii) aeration only during the night when the cost of energy is cheaper. Although lagooning can represent a suitable natural solution for the treatment of CWWs (Zema et al., 2016), water is lost thus not allowing its reuse.

Among the environmental factors affecting extensive treatments, the temperature is one of the main having a significant effect on depuration performances. Basically, increase in the temperature of the wastewater caused a change in solubility of oxygen in water (decrease in the saturation concentration Cs), acceleration of the process of the oxygen adsorption, the activity rate of bacteria and the rate of gases which are transferred to and from water (Alisawi, 2020). In general, the higher removal performances in extensive treatment systems could be obtainable during the warm periods (Kadlec and Reddy, 2001). Zema et al. investigated the effect of temperature in aerated ponds (Zema et al., 2012) and observed that the differences between for the removal rate of COD during the autumn-winter period compared to summer period were significant, so confirming the significant influence of temperature. Because the maximum production of CWWs is during the colder months, performances of such systems could be affected by low temperature. Nevertheless, the greater effect of temperature in extensive treatments is on the nutrients removal (nitrogen and phosphorous) (Alisawi, 2020), thus considering the absence of such elements in CWWs, the effect of temperature is of lesser importance.

In addition to the temperature, even precipitations play a crucial role in the operation of extensive treatment. A previous study observed that rainfall improved final effluent water quality of an aerobic lagoon system, although this was shown to be through dilution rather than improvement of treatment efficacy. Specifically, following precipitation events the contaminant removals were negatively impacted in the aerobic lagoon, whereas the removal rates were increased for anaerobic condition with the rainfall dilution (Alisawi, 2020).

3.5 Agricultural reuse of CWWs

Water is a critical input for agricultural production and plays an important role in food security. Irrigated agriculture represents 20 percent of the total cultivated land and contributes 40 percent of the total food produced worldwide (Ashley and Gruère, 2021). Due to population growth, urbanization, and climate change, the competition for water resources is expected to increase, with a particular impact on agriculture. Moreover, at the same time, the demand of water for the agricultural production to assure food for the increasing world population is expected to increase (El-Zanfaly, 2015).

The agricultural sector has proved to be the most suitable for the use of wastewater. Indeed, the application of wastewater for crop irrigation has grown a lot in recent years reaching about 20 million ha of irrigated land worldwide (Khalid et al., 2018).

According to Barbagallo et al. (2012) the water demand for irrigation is not satisfied properly in some areas of the Mediterranean basin due to the increase of adverse conditions such as drought, degradation of water body quality and ever-growing citizen demand.

Several factors contribute to define the correct use of wastewater. Wastewater originated from industrial, commercial, domestic, and dairy farm show different composition and variability in quantitative and quality aspects. This may have implications on the wastewater impact on the soil, which depends on soil characteristics, plant species and nature of wastewaters (El-Zanfaly, 2015). Thus, to use these effluents for agricultural practice, it is necessary to have knowledge of climatic, pedological and cultural conditions of a specific territory as well as wastewater characteristics (Bonari et al., 2007). Holding nutrients essential for plant growth such as nitrogen, phosphorus and potassium, as well as soluble organic matter (Table 1), their use, as they are, for crop irrigation could enhance soil fertility and crop production. Such an aspect is of paramount importance as on the one hand it allows to close the nutrients cycle and, on the other hand, to add organic matter to soil. Moreover, the use of not treated CWWs in agriculture for crop irrigation may be a valid alternative to their treatment in plant (Zema et al., 2019), if allowed by regulations. However, studies focusing on the effects of CWWs on soil fertility and crop growth are very few.

Recently, Ioppolo et al. (2020) investigated the effects of not treated CWWs on soil chemical properties and microbial community at laboratory scale. Lemon, orange and tangerine wastewaters, diluted with water at the rate of 1/3 or 2/3 or as they were (3/3), were applied once to soil samples to bring them at 50% of the water holding capacity. Soils were analysed at three different times during the 56 days of incubation since CWWs addition. Soil reaction decreased from 2 to 3 pH units following the addition of CWWs but, after 7 days, it recovered reaching values of the control (distilled water). The authors attributed such a reduction to the high content of organic acids in CWWs. At the same time, also electrical conductivity showed a transient increase and, therefore, the Authors suggested the need of monitoring the electrical conductivity (EC) if CWWs are added repeatedly.

Total and labile organic C increased following the addition of CWWs proportionally to the amount stored in the different CWWs (Ioppolo et al., 2020). Such an increase was, as for pH and EC, ephemeral although after 56 days of incubation soil moistened with not diluted orange wastewater had more organic C than the control. Total and extractable organic C increased following the addition of CWWs proportionally to the amount stored in the different CWWs. The increase of total and labile organic C following the addition of CWWs, in turn, stimulated microbial biomass and activity (CO_2 emission) although in ephemeral way (Ioppolo et al., 2020). Indeed, soil microorganisms live generally in oligotrophic conditions, thus when fresh organic substrates are added, such as those holding in CWWs, they restart their activity (Laudicina et al., 2012, 2013).

Based on the above results, Ioppolo et al. (2020) suggested a possible role of CWWs in sustainable farming. However, such a possibility has to be properly evaluated considering repeated addition of

CWWs, CWWs production time vs. crop needs, organic matter and minerals addition, and different type of soil and crops.

4. CWWs: costs and benefits

The reuse of wastewater lies within the principle of the circular economy model, which provides the recovery of resources considered as waste, achieving at the same time decrease of waste disposal and develop of value-added products (Corsino et al., 2021a).

Financial advantages occur in wastewater reuse throughout correct agronomic and processing operations aimed at the exploitation of wastewater for supporting natural water sources and reducing fertilizer costs, because of higher content in nutrients and the possibility to cultivate multiple crops with the greater water productivity (El-Zanfaly, 2015). The high content of nutrients in the wastewaters makes them particularly suitable for the irrigation of crops such as citrus and olives in Gaza district, resulting in a 70% reduction of fertilization costs and an increase in profits (Nassar, 2008). A recent study performed in Morocco assessed the economic feasibility of the irrigation and nutrition of citrus plants by using treated wastewaters (Oubelkacem et al., 2020). Cost-effectiveness of agronomic use of wastewater depends on the transfer phase from the processing industry to land application. Indeed, if CWWs are carried in small-medium distances and soils are in proper conditions, the agricultural utilization of this water could be cost-effective solution (Zema et al., 2012). Moreover, results show that the main obstacle to the use of treated wastewaters is linked to their higher cost, due to the treatment process, compared to fresh water (0.23 € m^{-3} vs 0.15 € m^{-3}). Thus, a reduction in the price could encourage their use on the 59% of the cultivated area. In terms of costs, a significant element is represented by the type of treatment performed on the wastewater. Relating to treatment of 4 million cubic meters (mcm)/year, the activated sludge treatment cost is about € 0.18 m^{-3} (per annum), with an addition of € 0.12 m^{-3} annually for nitrification-denitrification stage (Haruvy, 1997). In particular, as emphasized by

Navarro et al. (2008), evaluating the feasibility of a pilot plant for the treatment of wastewater from the lemon processing industry, the treatment cost is mainly related to the energy cost used for optimal oxygen transfer in the plant (70% of the operating costs). In light of this, Guzmán et al. (2016) found that the adoption of a photo-Fenton powered by renewable energy sources (solar) is a promising techniques for the treatment of CWW with a cost of 13.8 € m^{-3}, which include both the cost of operation and amortization, lower than that detected for conventional treatment processes. With a view to optimizing processes and reducing the volume of water arising from the citrus fruit processing process, Shen et al. (2021), by improving segment membrane removal process, obtain a processing water rich in electrolytes, pectin and flavonoids usable as drinkable beverages at low costs. As the authors themselves point out, although the cost of the new membrane is higher than the conventional one, the system allows for production of new electrolyte beverages with high health benefits and profitable on the market. It is reasonable thinking that the lower the treatment cost, the greater the interest in their use. However, this concept clashes with possible negative effects on the environment and in particular on groundwater pollution. As emphasized by Haruvy, (2005) the treatment cost of wastewater reflects the environmental costs linked to the groundwater pollution. Whatever the case, if it is decided to deal with wastewater, it is desirable to conduct an analysis of costs, risks, and benefits (Haruvy, 1997). In addition to the economic dimension, unquestionably important for the potential reuse of CWWs in agriculture, the environmental dimension associated with the recovery of wastewater, currently considered a waste, and the nutrients held which can improve soil fertility must be considered. The reuse of treated or not treated CWWs in agriculture represents, indeed, a strategic solution in line with the circular bioeconomy paradigm where a waste product derived from material of biological origin becomes a resource by improving eco-efficiency, reducing the demand for fertilizers, and enhancing the waste stream.

4.1 Advantages of CWWs reuse

The reuse of CWWs shows environmental, agronomic, and economic advantages. In arid and semiarid environment, agricultural production is limited by the scarcity of water or by its unsuitability for crop irrigation due to high concentration of soluble salts (Ungureanu et al., 2020). Thus, the use of wastewaters may represents a compelling necessity (Barbagallo et al., 2012). Using wastewaters for irrigation could avoid an increasingly massive subtraction of natural sources of water from the environment, thus allowing its full use for civil and industrial purposes (Barbagallo et al., 2012). Furthermore, the use of wastewaters agrees with the principles of the circular economy model in both solid and liquid wastes management practices because it provides the simultaneous minimization of waste disposal and generation of value-added products (Lee et al., 2014).

From the agronomic point of view, the reuse of CWWs is advantageous because allows to supply, at the same time, water, organic matter and mineral plant nutrients (Laudicina et al., 2013). CWWs are rich of low molecular weight organic substrates readily available for soil microorganisms. Indeed, recently, Ioppolo et al. (2020) demonstrated that the addition of lemon, orange and tangerine wastewaters stimulated soil microbial biomass and activity even when they were diluted before to be applied. Such an aspect is of paramount importance because it improves the nutrient cycling (Laudicina et al., 2012). On the other hand, the great amount of carbohydrates they hold may work as an organic cement, thus improving soil aggregation and enhancing soil fertility (Palazzolo et al., 2019; Ren et al., 2022). Among the main mineral plant nutrients supplied by CWWs, all nitrogen, phosphorus and potassium are the most abundant. Thus, when CWWs are used for crops irrigation, supply of mineral fertilizers can be rescaled to take into account the amount of mineral nutrients added by CWWs.

From an economic point of view, the reuse of CWWs can be advantageous, both for the citrus processing industry and farms. The former, supplying CWWs to farmers, can save the cost for their treatment and displacement, the latter, instead, can reduce their operating cost not paying money to buy water. In addition to the above advantages, since CWWs are available at the soil surface, farmers may reduce the cost to pump the volume of water needed for irrigation practice (Jaramillo and Restrepo, 2017). Finally, the application of CWWs on soil provides nutrients reducing inorganic fertilizers rates required for plants growth. The amount of nutrients that can be reached, considering a release of wastewater approximately of 5,000 m^3 ha^{-1} year, is almost 250 kg ha^{-1} for N, 50 kg ha^{-1} for P and 150 kg ha^{-1} for K. Moreover, CWWs can provide some micronutrients such as B, Fe, Al, Zn, Cu (Becerra-Castro et al., 2015). These CWW characteristics inevitably contribute to reducing the operating costs related to the purchase of fertilizers.

4.2 Disadvantages of CWWs reuse

As for advantages, also disadvantages can be environmental, agronomic and economic.

Environmental disadvantages of CWWs reuse are limited to the possible higher mobility of heavy metals due to their high acidity. Indeed, organic acids held by CWWs may increase heavy metals mobility by forming chelates (Violante et al., 2010) or by speeding up silicates alteration, thus making free aluminium hydroxides (Qin et al., 2018).

The decrease of the pH and the concomitant increase in electrical conductivity (Ioppolo et al., 2020) are the two main disadvantages from an agronomic point of view because both limit the range of cultivable agricultural crops. However, if soil has a good buffer capacity, small changes or rapidly recover of pH is expected (Ioppolo et al., 2020), thus doing such disadvantage transient.

According to Leverenz et al. (2011), however, the major constraints to reuse CWWs are noticed in (i) the long distance between the treatment facility and the agricultural lands, (ii) the construction costs of the pipe system for water displacement and, (iii) the necessary storage of CWWs during winter season, considering that they are produced in a period when there is not a high demand of water for crop growth (Leverenz et al., 2011). Other constraints may be (i) higher costs of treatment processes and reclaimed wastewater; (ii) protection of environment and human health; (iii) inadequate regulations to reuse of wastewater; (iv) higher costs for personnel and monitoring equipment; (v) lack of proper cooperation between authorities on the treatment and reuse of wastewater; (vi) distrust of farmers and consumers on this practice (El-Zanfaly, 2015). Moreover, fragmentation of the regulatory environment in the field of CWW reclamation could limit its spread across Europe. Removing this fragmentary approach might provide better improvement of public perception and raising confidence for wastewater reuse.

5. Concluding remarks and future perspectives

The industrial processing involving citrus fruits generates high amount of CWWs that have to be properly disposed. This literature review analysis highlights the numerous opportunities associated with the use of CWWs but also the most common obstacles. The latter related in a specific way to the high disposal costs, suggesting the necessity to find alternatives that allow companies to make a profit or, otherwise, to reduce costs, without neglecting the possible environmental implications of wastewater use. The alternatives to disposal may be the reuse of CWWs for agricultural purpose, after their exploitation for chemicals recover. The advantages of such alternative far outweigh the disadvantages because, firstly, water is completely recovered and, secondly, organic matter and mineral nutrients are added to soil thus improving soil fertility and allowing the closure of the nutrient cycle. In such a way, the reuse of CWWs for agricultural purpose fits with the new guidelines of the European Union about the circular bioeconomy, allowing the transition from the take-make-use-dispose model to the take-make-use-reuse one. On the other side, CWWs subject to treatment processes can give rise to high value by-products, which can compensate high costs necessary for their treatment. Despite these potentialities, to date, very few studies evaluated the economic feasibility of the use of CWWs in agriculture, addressed to understand their impact on the management costs of companies, or the opportunities related to the production of high value-added compounds.

In light of this review, future research should focus on parameters set up during the aerobic digestion for reducing sludge production, the effect of repeated addition of CWWs on soil chemical and biochemical properties, and crop yield, with a particular attention to the dynamics of heavy metals. In addition, economic and environmental feasibility analyses of the potential solutions for the use of CWWs are necessary to encourage green investments in the sector from a circular bio-economy perspective. From this point of view, and in the case of the use of CWWs for agricultural purposes, it could be interesting to estimate the market value of nutrients and organic matter added to the soil possibly replacing those that the farmer would have had to use, and the impact on the reduction of operating costs for this replacement. Furthermore, with reference to the treatment of CWWs to obtain valuable by-products, it is essential to enrich the empirical literature of studies on the economic analysis of transformation or treatment processes, in order to provide entrepreneurs with useful information and solid data that may justify their investments.

Based on above considerations, the best environmental and economic way to process CWWs could be that reported in Figure 3. Thus, after chemicals recovery by biorefinery, wastewaters should be directly used for crop irrigation if allowed by regulations or addressed to treatment plant. The latter way should be preferred when CWWs cannot be directly applied to soil due to lack of concomitance between CWWs production and crop needs. In such a way, treated wastewater should be reused after tertiary treatments for crop irrigation, whereas sludges should be undergone to dewatering treatment before being reused as organic amendment to improve soil fertility.

Finally, conclusions emerging from this review invite European institutions and each Member State to promote common and specific legislations to overcome the fragmentation of the regulatory framework regarding CWW reuse.

References

Alisawi, H.A.O., 2020. Performance of wastewater treatment during variable temperature. Appl.

Water Sci. 10, 1–6. doi:10.1007/s13201-020-1171-x

Andiloro, S., Bombino, G., Denisi, P., Folino, A., Zema, D.A., Zimbone, S.M., 2021. Depuration performance of aerated tanks simulating lagoons to treat olive oil mill wastewater under different airflow rates, and concentrations of polyphenols and nitrogen. Environ. - MDPI 8 (8), 70. doi:10.3390/environments8080070

Andiloro, S., Bombino, G., Tamburino, V., Zema, D.A., Zimbone, S.M., 2013. Aerated lagooning of agro-industrial wastewater: depuration performance and energy requirements. J. Agric. Eng. 44, 0–5. doi:10.4081/jae.2013.s2.e166

Argiz, L., Fra-Vázquez, A., del Río, Á.V., Mosquera-Corral, A., 2020. Optimization of an enriched mixed culture to increase PHA accumulation using industrial saline complex wastewater as a substrate. Chemosphere 247. doi:10.1016/j.chemosphere.2020.125873

Ashley, C., Gruère, G., 2021. 7th Roundtable on Financing Agricultural Water, Sustainable use of water for agriculture - Co-convened with FAO 27-28 January 2021 1–18.

Aziz, T.N.A.T., Tajuddin, R.M., Kamarun, D., Kordi, N.E., Malini, R., 2018. Citrus fruit waste leachate treatment by using newly developed flat sheet membrane. AIP Conf. Proc. 2020. doi:10.1063/1.5062671

Barbagallo, S., Cirelli, G.L., Consoli, S., Licciardello, F., Marzo, A., Toscano, A., 2012. Analysis of treated wastewater reuse potential for irrigation in Sicily. Water Sci. Technol. 65, 2024–2033. doi:10.2166/wst.2012.102

Barbusiński, K., Kościelniak, H., 1995. Influence of substrate loading intensity on floc size in activated sludge process. Water Res. 29, 1703–1710. doi:10.1016/0043-1354(94)00326-3

Battista, F., Remelli, G., Zanzoni, S., Bolzonella, D., 2020. Valorization of Residual Orange Peels: Limonene Recovery, Volatile Fatty Acids, and Biogas Production. ACS Sustain. Chem. Eng. 8, 6834–6843. doi:10.1021/acssuschemeng.0c01735

Becerra-Castro, C., Lopes, A.R., Vaz-Moreira, I., Silva, E.F., Manaia, C.M., Nunes, O.C., 2015. Wastewater reuse in irrigation: A microbiological perspective on implications in soil fertility and human and environmental health. Environ. Int. 75, 117–135. doi:10.1016/j.envint.2014.11.001

Bonari, E., Ercoli, L., Silvestri, N., Carcea, G., Barresi, F., 2007. Linee guida per l’utilizzazione agronomica delle acque di vegetazione e delle acque reflue da aziende agroalimentari. Agenzia per la protezione dell’ambiente e per i servizi tecnici (APAT), Rome, Manuali e linee guida ISBN: 978-88-448-0301-8.

Bousbia, N., Vian, M.A., Ferhat, M.A., Meklati, B.Y., Chemat, F., 2009. A new process for extraction of essential oil from Citrus peels: Microwave hydrodiffusion and gravity. J. Food Eng. 90, 409–413. doi:10.1016/j.jfoodeng.2008.06.034

Bozzano, G., Raymo, M., Manenti, F., Rulli, M.C., Girotto, F., Piazza, L., 2021. Prompting sustainability in the citrus derivates industry: A case study. Clean. Eng. Technol. 4, 100127. doi:10.1016/j.clet.2021.100127

Calabrò, P.S., Fazzino, F., Sidari, R., Zema, D.A., 2020. Optimization of orange peel waste ensiling for sustainable anaerobic digestion. Renew. Energy 154, 849–862. doi:10.1016/j.renene.2020.03.047

Calabrò, P.S., Pontoni, L., Porqueddu, I., Greco, R., Pirozzi, F., Malpei, F., 2016. Effect of the concentration of essential oil on orange peel waste biomethanization: Preliminary batch results. Waste Manag. 48, 440–447. doi:10.1016/j.wasman.2015.10.032

Calabrò, P.S., Pontoni, L., Porqueddu, I., Greco, R., Pirozzi, F., Malpei, F., Rigby, H., Smith, S.R., TeKippe, R.J., Thevendiraraj, S., Klemeš, J., Paz, D., Aso, G., Cardenas, G.J., Rosas-Mendoza, E.S., Méndez-Contreras, J.M., Martínez-Sibaja, A., Vallejo-Cantú, N.A., Alvarado-Lassman, A., Corsino, S.F., Di Trapani, D., Torregrossa, M., Viviani, G., Akratos, C.S., Tekerlekopoulou, A.G., Vayenas, D. V., Zema, D.A., Fòlino, A., Zappia, G., Calabrò, P.S., Tamburino, V., Zimbone, S.M., Koppar, A., Pullammanappallil, P., Martín, M.A., Siles, J.A., Chica, A.F., Martín, A., Ruiz, B., Flotats, X., Zema, D.A., Andiloro, S., Bombino, G., Tamburino, V., Sidari, R., Caridi, A., Fagbohungbe, M.O., Herbert, B.M.J., Hurst, L., Li, H., Usmani, S.Q., Semple, K.T., 2018. Agro-industrialwastewater treatment with decentralized biological treatment methods. Waste Manag. 33, 8993–8999. doi:10.1016/j.biortech.2016.04.106

Carawan, R., Chambers, V., Zall, R.R., Wi, R.H., 1979. Fruit and Vegetable Water and Management. Annual Report n. AM-18E.

Collivignarelli, M.C., Abbà, A., Miino, M.C., Torretta, V., 2019. What advanced treatments can be used to minimize the production of sewage sludge in WWTPs? Appl. Sci. 9, 2650. doi:10.3390/app9132650

Corsino, S.F., Di Trapani, D., Capodici, M., Torregrossa, M., Viviani, G., 2021a. Optimization of acetate production from citrus wastewater fermentation. Water Resour. Ind. 25, 100140. doi:10.1016/j.wri.2021.100140

Corsino, S.F., Di Trapani, D., Torregrossa, M., Viviani, G., 2018. Aerobic granular sludge treating high strength citrus wastewater: Analysis of pH and organic loading rate effect on kinetics, performance and stability. J. Environ. Manage. 214, 23–35. doi:10.1016/j.jenvman.2018.02.087

Corsino, S.F., Di Trapani, D., Torregrossa, N., Piazzese, D., 2021b. Preliminary evaluation of biopolymers production by mixed microbial culture from citrus wastewater in a MBR system using respirometric techniques. J. Water Process Eng. 41, 102003. doi:10.1016/j.jwpe.2021.102003

Corsino, S.F., Di Trapani, D., Traina, F., Cruciata, I., Scirè Calabrisotto, L., Lopresti, F., La Carrubba, V., Quatrini, P., Torregrossa, M., Viviani, G., 2022. Integrated production of biopolymers with industrial wastewater treatment: Effects of OLR on process yields, biopolymers characteristics and mixed microbial community enrichment. J. Water Process Eng. 47, 102772. doi:10.1016/j.jwpe.2022.102772

Di Trapani, D., Corsino, S.F., Torregrossa, M., Viviani, G., 2019. Treatment of high strength industrial wastewater with membrane bioreactors for water reuse: Effect of pre-treatment with aerobic granular sludge on system performance and fouling tendency. J. Water Process Eng. 31, 100859. doi:10.1016/j.jwpe.2019.100859

Directive 91/271/EEC, 1991. The urban waste water treatment directive. Available online on https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31991L0271.

Edwards, D.C., Norman, P.E., 2015. Best practices for management of wastewater treatment operations during extended refinery shutdowns, in: 88th Annual Water Environment Federation Technical Exhibition and Conference, WEFTEC 2015. doi:10.2175/193864715819539966

El-Zanfaly, H.T., 2015. Wastewater reuse in agriculture: a way to develop the economies of arid regions of the developing countries. J. Environ. Prot. Sustain. Dev. 1, 144–158.

FAO, 2020. Citrus Fruit Fresh and Processed Statistical Bulletin. doi:10.5860/choice.36-2167

Fazzino, F., Mauriello, F., Paone, E., Sidari, R., Calabrò, P.S., 2021. Integral valorization of orange peel waste through optimized ensiling: Lactic acid and bioethanol production. Chemosphere 271. doi:10.1016/j.chemosphere.2021.129602

Folino, A., Tamburino, V., Zappia, G., Zema, D.A., Zimbone, S.M., 2018. Valorisation of Citrus Processing Waste : a Review. Waste Manag. 80, 252–273.

Garcia, C.F.H., de Souza, R.B., de Souza, C.P., Fontanetti, C.S., 2019. Effluent from Citrus Industry: Toxic Parameters of Orange Vinasse. Water. Air. Soil Pollut. 230. doi:10.1007/s11270-019-4260-4

Giesen, A., van Loosdrecht, M., de Bruin, B., van der Roest, H., Pronk, M., 2013. Full-scale Experiences with Aerobic Granular Biomass Technology for Treatment of Urban and Industrial Wastewater, in: International Water Week.

Guzmán, J., Mosteo, R., Sarasa, J., Alba, J.A., Ovelleiro, J.L., 2016. Evaluation of solar photo-Fenton and ozone based processes as citrus wastewater pre-treatments. Sep. Purif. Technol. 164, 155–162. doi:10.1016/j.seppur.2016.03.025

Haruvy, N., 2005. Land Use and Water Management in Israel- Economic and Environmental

Analysis of Sustainable Reuse of Wastewater in Agriculture. 45th Congr. Eur. Reg. Sci. Assoc. L. Use Water Manag. Sustain. Netw. Soc. 23-27 August 2005.

Haruvy, N., 1997. Agricultural reuse of wastewater: Nation-wide cost-benefit analysis. Agric. Ecosyst. Environ. 66, 113–119. doi:10.1016/S0167-8809(97)00046-7

Hawash, S., Hafez, A.J., El‐Diwani, G., 1988. Citrus Processing Wastewater Treatment. Chemie Ing. Tech. 60, 128–130. doi:10.1002/cite.330600214

Hunter, S.M., Blanco, E., Borrion, A., 2021. Expanding the anaerobic digestion map: A review of intermediates in the digestion of food waste. Sci. Total Environ. 767, 144265. doi:10.1016/j.scitotenv.2020.144265

Indelicato, M., Tamburino, V., Zimbone, S.M., 1997. Prove di invaso ed irrigazione con acque reflue dell’industria agrumaria, in: Proceedings of "Convegno Nazionale Di Ingegneria Agraria. Ancona 11-12 September.

Ioppolo, A., Laudicina, V.A., Badalucco, L., Saiano, F., Palazzolo, E., 2020. Wastewaters from citrus processing industry as natural biostimulants for soil microbial community. J. Environ. Manage. 273, 111137. doi:10.1016/j.jenvman.2020.111137

Jaramillo, M.F., Restrepo, I., 2017. Wastewater reuse in agriculture: A review about its limitations and benefits. Sustain. 9 (10), 1734. doi:10.3390/su9101734

Jenkins, D., Richard, M.G., Daigger, G.T., 2003. Manual on the Causes and Control of Activated Sludge Bulking, Foaming and Other Solids Separation Problems. IWA, London ISBN 1566706475.

Kadlec, R.H., Reddy, K.R., 2001. Temperature Effects in Treatment Wetlands. Water Environ. Res. 73, 543–557. doi:10.2175/106143001x139614

Karim, A., Islam, M.A., Mohammad Faizal, C.K., Yousuf, A., Howarth, M., Dubey, B.N., Cheng, C.K., Rahman Khan, M.M., 2019. Enhanced Biohydrogen Production from Citrus Wastewater Using Anaerobic Sludge Pretreated by an Electroporation Technique. Ind. Eng. Chem. Res. 58, 573–580. doi:10.1021/acs.iecr.8b03586

Khalid, S., Shahid, M., Natasha, Bibi, I., Sarwar, T., Shah, A.H., Niazi, N.K., 2018. A review of environmental contamination and health risk assessment of wastewater use for crop irrigation with a focus on low and high-income countries. Int. J. Environ. Res. Public Health 15, 1–36. doi:10.3390/ijerph15050895

Killham, K., 1994. Soil ecology. Cambridge University Press. doi:10.1017/9780511623363

Kimball, D., 1999. Citrus Processing :A Complete Guide, 2nd ed, Materials Research Bulletin.

Klemes, J.J., 2012. Industrial water recycle/reuse. Curr. Opin. Chem. Eng. 1, 238–245. doi:10.1016/j.coche.2012.03.010

Koppar, A., Pullammanappallil, P., 2013a. Anaerobic digestion of peel waste and wastewater for on site energy generation in a citrus processing facility. Energy 60, 62–68. doi:10.1016/j.energy.2013.08.007

Koppar, A., Pullammanappallil, P., 2013b. Anaerobic digestion of peel waste and wastewater for on site energy generation in a citrus processing facility. Energy 60, 62–68. doi:10.1016/j.energy.2013.08.007

Kruzic, A.P., Liehr, S.K., 2008. Natural Treatment and Onsite Systems. Water Environ. Res. 80, 1206–1224. doi:10.2175/106143008x328608

Laudicina, V., Palazzolo, E., Badalucco, L., 2013. Natural Organic Compounds in Soil Solution: Potential Role as Soil Quality Indicators. Curr. Org. Chem. 17, 2991–2997. doi:10.2174/13852728113179990120

Laudicina, V.A., Barbera, V., Gristina, L., Badalucco, L., 2012. Management practices to preserve soil organic matter in semiarid mediterranean environment, in: Soil Organic Matter: Ecology, Environmental Impact and Management. New York : Nova Science Publishers, Inc.., pp. 39–61.

Lee, W.S., Chua, A.S.M., Yeoh, H.K., Ngoh, G.C., 2014. A review of the production and applications of waste-derived volatile fatty acids. Chem. Eng. J. 235, 83–99. doi:10.1016/j.cej.2013.09.002

Leverenz, H.L., Tchobanoglous, G., Asano, T., 2011. Direct potable reuse: A future imperative. J. Water Reuse Desalin. 1, 2–10. doi:10.2166/wrd.2011.000

Libutti, A., Gatta, G., Gagliardi, A., Vergine, P., Pollice, A., Beneduce, L., Disciglio, G., Tarantino, E., 2018. Agro-industrial wastewater reuse for irrigation of a vegetable crop succession under Mediterranean conditions. Agric. Water Manag. 196, 1–14. doi:10.1016/j.agwat.2017.10.015

Lobato, J., González del Campo, A., Fernández, F.J., Cañizares, P., Rodrigo, M.A., 2013. Lagooning microbial fuel cells: A first approach by coupling electricity-producing microorganisms and algae. Appl. Energy 110, 220–226. doi:10.1016/j.apenergy.2013.04.010

Lukitawesa, Eryildiz, B., Mahboubi, A., Millati, R., Taherzadeh, M.J., 2021. Semi-continuous production of volatile fatty acids from citrus waste using membrane bioreactors. Innov. Food Sci. Emerg. Technol. 67, 102545. doi:10.1016/j.ifset.2020.102545

Lukitawesa, Wikandari, R., Millati, R., Taherzadeh, M.J., Niklasson, C., 2018. Effect of effluent recirculation on biogas production using two-stage anaerobic digestion of citrus waste. Molecules 23, 1–11. doi:10.3390/molecules23123380

Mak, T.M.W., Xiong, X., Tsang, D.C.W., Yu, I.K.M., Poon, C.S., 2020. Sustainable food waste management towards circular bioeconomy: Policy review, limitations and opportunities. Bioresour. Technol. 297, 122497. doi:10.1016/j.biortech.2019.122497

Martín, M.A., Siles, J.A., Chica, A.F., Martín, A., 2010. Biomethanization of orange peel waste. Bioresour. Technol. 101, 8993–8999. doi:10.1016/j.biortech.2010.06.133

Matamoros, V., Rodríguez, Y., Albaigés, J., 2016. A comparative assessment of intensive and extensive wastewater treatment technologies for removing emerging contaminants in small communities. Water Res. 88, 777–785. doi:10.1016/j.watres.2015.10.058

Mateus, A., Torres, J., Marimon-Bolivar, W., Pulgarín, L., 2021. Implementation of magnetic bentonite in food industry wastewater treatment for reuse in agricultural irrigation. Water Resour. Ind. 26. doi:10.1016/j.wri.2021.100154

Metcalf, Eddy, 2015. Wastewater Engineering Treatment and Resource Recovery. 5th edition.

ISBN 9780073401188 / 0073401188.

Molinos-Senante, M., Hernández-Sancho, F., Sala-Garrido, R., Cirelli, G., Guo, J., Fu, X., Andrés Baquero, G., Sobhani, R., Nolasco, D.A., Rosso, D., 2016. Trade-off between carbon emission and effluent quality of activated sludge processes under seasonal variations of wastewater temperature and mean cell retention time - European Union Commission, Science of the Total Environment.

Narendranath, N. V., Thomas, K.C., Ingledew, W.M., 2001. Effects of acetic acid and lactic acid on the growth of Saccharomyces cerevisiae in a minimal medium. J. Ind. Microbiol. Biotechnol. 26, 171–177. doi:10.1038/sj.jim.7000090

Nassar, A.G., 2008. Effect of Citrus by-Products Flour Incorporation on Chemical , Rheological and Organolepic Characteristics of Biscuits. Sci. Technol. 4, 612–616.

Navarro, A.R., Lopez, Z.O., Maldonado, M.C., 2008. A pilot plant for the treatment of lemon industry wastewater. Clean Technol. Environ. Policy 10, 371–375. doi:10.1007/s10098-008-0152-9

Nemerow, N., 2007. Equalization and proportioning. Ind. Waste Treat. 45–51. doi:10.1016/b978-012372493-9/50039-9

Oubelkacem, A., Scardigno, A., Choukr-Allah, R., 2020. Treated Wastewater Reuse on Citrus in Morocco: Assessing the Economic Feasibility of Irrigation and Nutrient Management Strategies. Integr. Environ. Assess. Manag. 16, 898–909. doi:10.1002/ieam.4314

Palazzolo, E., Laudicina, V.A., Roccuzzo, G., Allegra, M., Torrisi, B., Micalizzi, A., Badalucco, L., 2019. Bioindicators and nutrient availability through whole soil profile under orange groves after long-term different organic fertilizations. SN Appl. Sci. 1, 1–11. doi:10.1007/s42452-019-0479-3

Parish, M.E., Braddock, R.J., Graumlich, T.R., 1986. Chemical and Microbial Characterization of Citrus Oil ‐ Mill Effluent. J. Food Sci. 51, 431–433. doi:10.1111/j.1365-2621.1986.tb11148.x

Qin, J., Enya, O., Lin, C., 2018. Dynamics of Fe, Mn, and Al liberated from contaminated soil by low-molecular-weight organic acids and their effects on the release of soil-borne trace elements. Appl. Sci. 8 (12), 2444. doi:10.3390/app8122444

Regulation EU 2020/741, 2020. Regulation (EU) 2020/741, Minimum requirements for water reuse. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX% 3A32019R1009.

Ren, C., Liu, K., Dou, P., Li, J., Wang, K., 2022. The Changes in Soil Microorganisms and Soil Chemical Properties Affect the Heterogeneity and Stability of Soil Aggregates before and after Grassland Conversion. Agriculture 12, 307. doi:10.3390/agriculture12020307

Rosas-Mendoza, E.S., Méndez-Contreras, J.M., Aguilar-Lasserre, A.A., Vallejo-Cantú, N.A., Alvarado-Lassman, A., 2020. Evaluation of bioenergy potential from citrus effluents through anaerobic digestion. J. Clean. Prod. 254, 1–11. doi:10.1016/j.jclepro.2020.120128

Rosas-Mendoza, E.S., Méndez-Contreras, J.M., Martínez-Sibaja, A., Vallejo-Cantú, N.A., Alvarado-Lassman, A., 2018. Anaerobic digestion of citrus industry effluents using an Anaerobic Hybrid Reactor. Clean Technol. Environ. Policy 20, 1387–1397. doi:10.1007/s10098-017-1483-1

Saadatinavaz, F., Karimi, K., Denayer, J.F.M., 2021. Hydrothermal pretreatment: An efficient process for improvement of biobutanol, biohydrogen, and biogas production from orange waste via a biorefinery approach. Bioresour. Technol. 341, 125834. doi:10.1016/j.biortech.2021.125834

Schimmenti, E., Borsellino, V., Galati, A., 2013. Growth of citrus production among the Euro-Mediterranean countries: Political implications and empirical findings. Spanish J. Agric. Res. 11, 561–577. doi:10.5424/sjar/2013113-3422

Sharma, K., Mahato, N., Cho, M.H., Lee, Y.R., 2017. Converting citrus wastes into value-added products: Economic and environmently friendly approaches. Nutrition 34, 29–46. doi:10.1016/j.nut.2016.09.006

Shen, S., Cheng, H., Liu, Y., Chen, Y., Chen, S., Liu, D., Ye, X., Chen, J., 2021. New electrolyte beverages prepared by the citrus canning processing water through chemical improvement. Food Chem. X 12, 100155. doi:10.1016/j.fochx.2021.100155

Shrivastava, V., Ali, I., Marjub, M.M., Rene, E.R., Soto, A.M.F., 2022. Wastewater in the food industry: Treatment technologies and reuse potential. Chemosphere 293. doi:10.1016/j.chemosphere.2022.133553

Strazzera, G., Battista, F., Garcia, N.H., Frison, N., Bolzonella, D., 2018. Volatile fatty acids production from food wastes for biorefinery platforms: A review. J. Environ. Manage. 226, 278–288. doi:10.1016/j.jenvman.2018.08.039

Suri, S., Singh, A., Nema, P.K., 2020. Current Applications of Citrus Fruit Processing Waste: A Scientific Outlook. Waste Manag. 11, 1–11. doi:10.1021/acssuschemeng.0c01735

Tamburino, V., Zema, D.A., Zimbone, S.M., 2007. Depuration Processes of Citrus Wastewater, in: CIGR Section VI International Symposium on Food and Agricultural Products: Processing and Innovations.

Torquato, L.D.M., Pachiega, R., Crespi, M.S., Nespeca, M.G., de Oliveira, J.E., Maintinguer, S.I., 2017. Potential of biohydrogen production from effluents of citrus processing industry using anaerobic bacteria from sewage sludge. Waste Manag. 59, 181–193. doi:10.1016/j.wasman.2016.10.047

Ungureanu, N., Vlăduț, V., Voicu, G., 2020. Water scarcity and wastewater reuse in crop irrigation. Sustain. 12, 1–19. doi:10.3390/su12219055

Vaish, B., Srivastava, V., Singh, P.K., Singh, P., Singh, R.P., 2020. Energy and nutrient recovery from agro-wastes: Rethinking their potential possibilities. Environ. Eng. Res. 25, 623–637. doi:10.4491/eer.2019.269

Valentino, F., Morgan-Sagastume, F., Fraraccio, S., Corsi, G., Zanaroli, G., Werker, A., Majone, M., 2015. Sludge minimization in municipal wastewater treatment by polyhydroxyalkanoate (PHA) production. Environ. Sci. Pollut. Res. 22, 7281–7294. doi:10.1007/s11356-014-3268-y

Violante, A., Cozzolino, V., Perelomov, L., Caporale, A.G., Pigna, M., 2010. Mobility and bioavailability of heavy metals and metalloids in soil environments. J. Soil Sci. Plant Nutr. 10, 268–292. doi:10.4067/S0718-95162010000100005

Wanner, J., 2017. Activated sludge separation problems, 2nd Edition. ISBN 9781780408637. doi:10.2166/9781780408644_053

Yadav, V., Sarker, A., Yadav, A., Miftah, A.O., Bilal, M., Iqbal, H.M.N., 2022. Integrated biorefinery approach to valorize citrus waste: A sustainable solution for resource recovery and environmental management. Chemosphere 293, 133459. doi:10.1016/j.chemosphere.2021.133459

Zema, D.A., Andiloro, S., Bombino, G., Caridi, A., Sidari, R., Tamburino, V., 2016. Comparing Different Schemes of Agricultural Wastewater Lagooning: Depuration Performance and Microbiological Characteristics. Water. Air. Soil Pollut. 227. doi:10.1007/s11270-016-3132-4

Zema, D.A., Andiloro, S., Bombino, G., Tamburino, V., Sidari, R., Caridi, A., 2012. Depuration in aerated ponds of citrus processing wastewater with a high concentration of essential oils. Environ. Technol. (United Kingdom) 33, 1255–1260. doi:10.1080/09593330.2011.618938

Zema, D.A., Calabro, P.S., Folino, A., Tamburino, V., Zappia, G., Zimbone, S.M., 2019. Wastewater management in citrus processing industries: An overview of advantages and limits. Water (Switzerland) 11, 2481. doi:10.3390/w11122481

Zema, D.A., Calabrò, P.S., Folino, A., Tamburino, V., Zappia, G., Zimbone, S.M., 2018. Valorisation of citrus processing waste: A review. Waste Manag. 80, 252–273. doi:10.1016/j.wasman.2018.09.024

Zhu, Ya, Zhai, Y., Li, S., Liu, Xiangmin, Wang, B., Liu, Xiaoping, Fan, Y., Shi, H., Li, C., Zhu, Yun, 2022. Thermal treatment of sewage sludge: A comparative review of the conversion principle, recovery methods and bioavailability-predicting of phosphorus. Chemosphere 291, 133053. doi:10.1016/j.chemosphere.2021.133053