

Edible seed oil waste: status quo and future perspectives

P. J. Welz 

ABSTRACT

Large volumes of process water and steam are required for extraction and refining of edible seed oils. Water usage in most industries has decreased over the years as increasing emphasis is being placed on water re-use in modern facilities. However, given the size of the edible seed oil industry globally, there is a lack of current quantitative data about water use and wastewater generation. As the world moves towards a circular economy and water becomes more scarce, it is imperative that the industry players provide meaningful input/output data in order to benchmark and identify areas for waste valorization. This review provides data currently available in the public domain on the specific wastewater intake and wastewater generation by the edible seed oil industry, highlighting the need for further data collection. In addition, wastewater quality and current and future wastewater treatment technologies are discussed, as well as the potential for valorization of solid waste and effluent from the industry, and potential avenues for future research.

Key words | edible oil, re-use, valorization, wastewater, water

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SELECTED ABBREVIATIONS

AWW	acid wastewater
EFO	edible fruit oils
ESO	edible seed oil
EVO	edible vegetable oil
SED	specific effluent discharge
SWI	specific water intake

INTRODUCTION

According to statistics published by the United States Department of Agriculture (USDA) Foreign Agricultural Service, the production of edible vegetable oil (EVO) has increased year-on-year over the past decade. The total volume is set to reach around 208 million metric tons (MT) in 2019 (USDA 2019). Palm oil, a fruit oil from Indonesia and Malaysia, constitutes more than one third of this amount (USDA 2019). Deforestation to make way for palm oil plantations in these countries is environmentally

contentious because this practice results in biodiversity losses and greenhouse gas emission increases (Malahayati & Masui 2018). Similarly, the diversion of arable land away from growing food crops to growing oilseeds for first generation biofuel production has sparked the ‘food vs fuel’ debate (Hassan *et al.* 2019). In a number of countries/regions, a significant percentage of seeds oils are cultivated specifically for biodiesel (Argentina (~70%), the European Union (~40%), Thailand (~70%) and Brazil (~35%), (USDA 2019)).

Edible seed oil (ESO) and edible fruit oil (EFO) make up the bulk of vegetable oils produced world-wide, but more research has been dedicated to remediation and valorization of palm oil and olive oil industry wastes than ESO wastes (Gibon *et al.* 2009; Lai *et al.* 2012). In some instances, including in Europe and South Africa (SA), extracted palm oil is imported and refined locally with other EVO, so some refineries cannot be strictly delineated into EVO or EFO facilities (Gibon *et al.* 2009; Schneider & Finkbeiner 2013; Welz *et al.* 2017). Nevertheless, because seeds have hard husks and fruits are relatively soft, overall processing for EFOs differs substantially from that for ESOs (Durnford 2008; Hamm *et al.* 2013; Savoie *et al.* 2013).

The ESO industry is resource, water, energy and waste intensive and, in many instances, wastes and by-products

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are not utilized to their full potential (Welz *et al.* 2017). In addition, there is a lack of data available from the ESO industry at large in the public domain (Schneider & Finkbeiner 2013). In order for the industry to set benchmarks, and for researchers to define realistic new avenues for investigation, it is imperative that reliable qualitative and quantitative data are available (Schneider & Finkbeiner 2013; Welz *et al.* 2017). To address the lack of primary data from the ESO industry, FEDOIL commissioned the establishment of a valid database of primary data from six companies belonging to the European vegetable oil and protein oil industry, and performed a life cycle assessment to determine the potential environmental impacts of the industry using a gate-to-gate approach (Schneider & Finkbeiner 2013). However, water usage was largely excluded, and wastewater treatment was not considered because insufficient data were collected to model the composition and emissions of an 'average' wastewater treatment process. A number of reports on the characteristics of ESO effluent are available in other reports, but those on specific water usage and effluent discharge are scanty, and, in many instances, outdated. This review provides the (limited) currently available information, and highlights the data gaps and potential avenues for research.

Processing of edible seed oils

Processing of seeds is divided into three phases: pre-treatment, separation, and refining (Figure 1). The steps that are applied are incumbent on site preferences and feedstock. After physical-mechanical pre-treatment to remove husks and debris, the oil is separated from the rest of the seed material by expelling (often referred to as pressing) and/or extraction. The residue obtained from expelling is known as an oilcake. Typically, expelling is followed by extraction of residual oil from the oilcake with high oil content seeds (e.g. sunflower, rapeseed/canola), while extraction alone (no expelling) is employed with low oil content seeds (e.g. soybeans). Extraction is accomplished using a solvent (usually commercial hexane, which is a mixture of hexane isomers). The solvent is recovered from the oil-solvent mixture (miscella) by distillation, and re-used (Durnford 2008; Hamm *et al.* 2013; Savoie *et al.* 2013).

Most crude ESO is then refined to prevent spoilage and to remove substances that may affect the taste, odour and appearance of the oils, including gums, waxes, free fatty acids (FFAs), pigments, aldehydes and ketones (Lai *et al.* 2012; Hamm *et al.* 2013). Most of the process water (direct and indirect) is used in these neutralization processes, the

most common of which are shown in Figure 1. In alkali (chemical) refining, the oil is usually conditioned using phosphoric acid (H_3PO_4), after which sodium hydroxide (NaOH) is mixed with the oil to saponify FFAs, neutralize H_3PO_4 and hydrate and saponify phospholipids; after a specified reaction time, the oil is mixed with hot water and the unwanted soapstock is split from the oil. Bleaching removes pigmented molecules, primary and secondary oxidation products, soaps and polyaromatics via electrostatic adsorption onto the surface of bentonite clays; deodorizing removes most of the volatile compounds responsible for off-odours, and pesticide residues by steam stripping at 160–260 °C (Hamm *et al.* 2013). A similar steam stripping process, distillation, also removes FFAs from oils that have been physically refined (i.e. have not been chemically neutralized) (Hamm *et al.* 2013).

Potential for valorization and re-use of edible oil solid waste

Although the main focus of this review pertains to wastewater, other by-products and wastes from the ESO industry are briefly discussed here. This is because when industries look to apply circular economy principles at a local level, all processes need to be assessed holistically in order to evaluate the potential for valorization, resource reduction, and re-use (Corona *et al.* 2019).

In a recent national survey (NATSURV) of the EVO in SA, it was ascertained that seed hulls and fines were traditionally re-used as low grade animal fodder or bedding, AWW was often used to make soap, and waxes were used in candle-making (Welz *et al.* 2017, Figure 1). Among others, there is potential for valorization of the hulls/fines, for example, as a component in structural materials, or for extraction of value-added products. Indeed, it has recently been shown that it may be viable to extract levoglucosan and/or furfural from bio-oils obtained from pyrolysed sunflower seed hulls (Casoni *et al.* 2019).

Bleaching clay is an expensive natural resource that is typically landfilled when spent, which means that there are economic and environmental incentives for re-use (Boukerroui *et al.* 2018). At the very least, the spent earth can be used as fuel in boilers (Pandey *et al.* 2003). Successful clay regeneration has been achieved using solvents, acids or alkalis (e.g. Boukerroui *et al.* 2018), but these methods generate potentially toxic ancillary liquid waste streams, and can have high operational costs (Oladosu *et al.* 2017). Sub-critical water extraction and sub-critical fluid extraction are more advanced technologies that have been shown to recover a

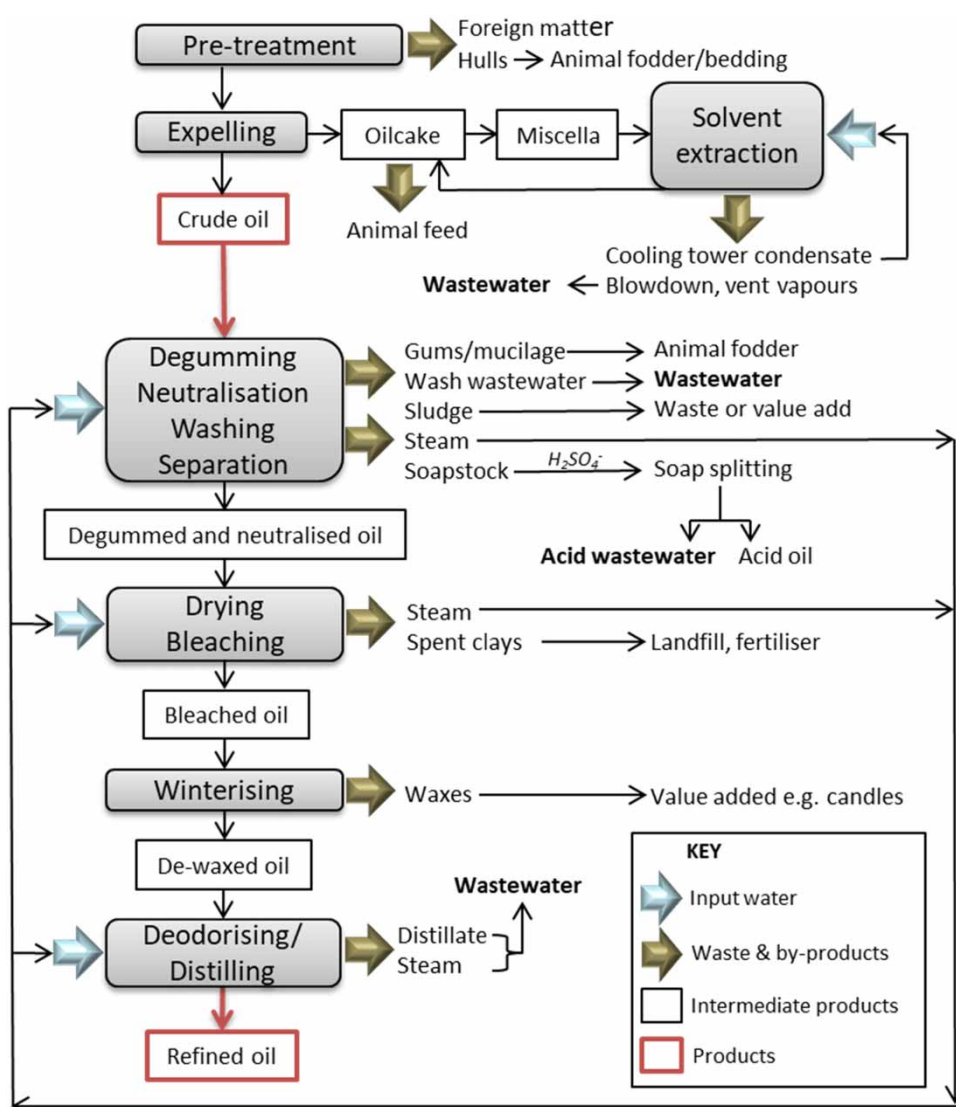


Figure 1 | Basic schematic of input water, and solid and liquid products, by-products and wastes from a typical edible seed oil processing facility (adapted from Welz *et al.* 2017).

fraction of the oil from bleaching clays, but none of the studies to date have considered re-use of the clay (Oladosu *et al.* 2017). There is a real need for research pertaining to (i) regeneration of bleaching clays using 'green' chemical/physicochemical methods with minimal ancillary waste, and/or (ii) more sustainable methods of bleaching, as with the use of boiler ash as an alternative bleaching agent, as recently been described by Lau *et al.* (2019). Ways to re-use or valorize other forms of solid waste such as spent nickel catalyst and deodorizer distillate should also be considered (Pandey *et al.* 2003). For example, Sherazi *et al.* (2016) has found that saponified deodorizer distillates contain large fractions of valuable nutraceuticals, including tocopherols and sterols.

Specific water intake

Pre-treatment of edible seeds is energy demanding, but has no direct water requirements for ESO processing (Hamm *et al.* 2013). Extraction and refining consume large volumes of water and generate effluent that is difficult to remediate. Benchmarks for water use are available (e.g. in the 2006 EU 'Best available technologies (BAT) in food, milk and drink industries' document and similar documents (BMU 2002; CIAA-FEDOIL 2002; EC-BAT 2006; World bank group 2015; EC-BAT 2019)). However, when interrogating the references, these all emanate from the same data originally published in 1986 (BMU 1986), which is not widely accessible. Around the same

time, Steffen *et al.* (1989) published specific water intake (SWI) data from 11 processing facilities in SA as part of an original National Survey (NATSURV) (Table 1). However, in a more recent NATSURV, oil facilities divulged robust data on SWI (Welz *et al.* 2017). FEDOIL, the umbrella body representing the European vegetable oil and protein oil industry commissioned TU Berlin to conduct a lifecycle assessment of oilseed crushing and refining by its members. Data were collected from six relevant European companies and a comprehensive document was published (Schneider & Finkbeiner 2013). The average SWI (water and steam) from three oilseed processing facilities were obtained and published (Table 1), but no details were provided in the document. Unfortunately, water use was not seen as a priority because the authors deemed the amount of process water to be relatively small when compared to other stages of the supply chain such as cultivation of oilseeds. They also motivated that there is currently no agreed standard on how to assess water use within the life cycle analysis method that they used (Schneider & Finkbeiner 2013). Although the authors stated that water consumption was 'out of the scope' of the study, they recommended that a future study be conducted on this aspect. While there is clearly a need to update industry benchmarks, it is difficult to extrapolate water usage goals from the limited data currently available in the public domain (Table 1).

Table 1 | Literature values for water intake for edible seed oil processing

Oil type	Process	Specific water intake (m ³ /MT oil)	References
Seed ^a	Crushing	2.6 (range: 2.1–3.1) (<i>n</i> = 11)	Steffen <i>et al.</i> (1989)
Seed ^a	Refining	3.8 (range: 3.2–4.6) (<i>n</i> = 11)	Steffen <i>et al.</i> (1989)
Rapeseed	Crushing	1.19 (<i>n</i> = 3)	Schneider & Finkbeiner (2013)
Rapeseed	Refining	0.67 (<i>n</i> = 3)	Schneider & Finkbeiner (2013)
Soybean	Crushing	2.60 (<i>n</i> = 3)	Schneider & Finkbeiner (2013)
Soybean	Refining	0.77 (<i>n</i> = 3)	Schneider & Finkbeiner (2013)
^a Seed	Refining	<1.5	Welz <i>et al.</i> (2017)
^a Seed	Physical refining	0.29	Welz <i>et al.</i> (2017)

^aTypes of seed not specified.

Specific wastewater generation

Refining typically generates larger volumes of effluent than pressing/extraction, provided cooling water is effectively recirculated (BMU 1986; Abdel-Gawad & Abdel-Shafy 2002; Hamm *et al.* 2013). Data on specific effluent discharge (SED) volumes from ESO processing are scant, and in most cases, dated (BMU 1986; Steffen *et al.* 1989). As with SWI, cited values can be traced back to data originally published in 1986 (BMU 1986). The total volume of effluent generated is provided in some more recent reports, but the amount of oil produced is not, so the SED cannot be calculated (e.g. Chipasa 2001; Dkhissi *et al.* 2018).

Of the limited data available, Steffen *et al.* (1989) reported an overall SED of 2.0 m³/MT oil for extraction and refining, but higher values (2.7 m³/MT oil) were reported more recently from an ESO factory in Egypt after the application of waste minimization measures (Abdel-Gawad & Abdel-Shafy 2002).

Only 1 of 17 vegetable processing facilities was willing to divulge data regarding SED volumes during a recent National Survey (NATSURV) in SA, despite offers to sign confidentially agreements (Welz *et al.* 2017). This general reluctance by the industry may be a factor for the lack of data available at a global level for both water use and wastewater generation. The ESO involved reported the highest SED volumes for solvent extraction (0.3 m³/MT oil), followed by chemical refining (0.15 m³/MT oil) and physical refining (0.15 m³/MT oil), while only 0.03–0.05 m³/MT oil was reported as being generated from soap-splitting (Welz *et al.* 2017). The latter is in stark contrast to the 1.0–1.5 m³/MT oil cited in the EU BAT document, and highlights the need for revision of the data to reflect the current status quo and allow the industry to benchmark realistically.

Wastewater quality

Cooling tower blow-down typically forms part of the general effluent, and is recognized as being relatively uncontaminated (Hamm *et al.* 2013). The refinery effluent (Figure 1) can be divided into two main categories: (i) acid wastewater (AWW) from soap splitting (chemical refining) and (ii) general process wastewater (GPWW) from either distilling (physical refining) or oil washing and deodorizing (chemical refining) that may or may not be combined with AWW. The AWW contains mainly FFAs and excess H₂SO₄ from soap splitting, while the GPWW typically contains large amounts of FFAs, as well as aromatics, residual gums, degumming acids (H₃PO₄ or citric acid), pesticides and soaps from

chemical refining. General wash-water and cooling tower blowdown may be combined with the GPWW before treatment or discharge, while the AWW may or may not be added to the combined stream (Welz *et al.* 2017). If large volumes of EVO effluent are discharged via municipal reticulation systems into domestic wastewater treatment systems, system performance can be negatively affected. In most cases, pollutant loads for incoming wastewater are set by municipal wastewater treatment plants, so that some form of treatment is required before discharge (Welz *et al.* 2017). The effluent is also hazardous if released into the environment. For example, in August 2019, a spill from an EVO processing facility in SA into a nearby river system resulted in an environmental disaster (<https://mg.co.za/article/2019-08-23-00-rivers-die-after-oil-chemical-spill>).

Literature values for key parameters in GPWW and AWW are provided in Table 2. The pH of the GPWW exhibits large inter- and intra-site variability because both acids (e.g. H_3PO_4 for degumming and conditioning and alkalis (NaOH for neutralization during chemical refining) are typically added. The pH variability is challenging for most effluent treatment technologies, so it is adjusted prior to treatment (Chipasa 2001; Abdel-Gawad & Abdel-Shafy 2002; Pandey *et al.* 2003; Azbar & Yonar 2004). Both the GPWW and AWW contain high concentrations of organics, with chemical oxygen demand (COD) concentrations of up to 15.4 g/L and 350 g/L being reported in GPWW (Aslan *et al.* 2009) and AWW (Roux-van der Merwe *et al.* 2005), respectively. Apart from one anomalous result (1.0, Pintor *et al.* 2014), the reported biological oxygen demand (BOD) to COD ratios range from 0.2 to 0.6, demonstrating that the effluent is only slowly to moderately biodegradable. Good correlations between COD, and oil and grease (OG) concentrations in ESO effluents have been demonstrated (Saatchi *et al.* 2001). Discounting two anomalous results for the COD:OG ratio (13.9 and 34.4; Aslan *et al.* 2009), the ratios of 1.1–7.3 reflect (as expected), high residual oil content in both GPWW and AWW. High total phosphate (TP) concentrations are found in ESO effluent from residual oil phosphatides from H_3PO_4 (if used for degumming). It is important to monitor sulfate (SO_4^{2-}) in the effluent from chemical refining because high concentrations of sulfuric acid (H_2SO_4) can be found from soap-splitting.

Wastewater treatment and valorization

Results of studies on the performance of full-scale conventional treatment systems, as well as laboratory scale studies are given in Table 3.

The high organic content in raw ESO effluent may suggest that biological treatment is an attractive option for organic removal, especially in cases where oils are emulsified and/or FFAs are saponified (Chipasa & Mędrzyca 2006). However, a number of researchers have shown that lipids remain in the treated effluent because they are both biodegraded and bio-synthesized simultaneously, and are also released during endogenous microbial decay (Chipasa & Mędrzyca 2008). While the conventional activated sludge (CAS) system used as a stand-alone has shown some success at laboratory scale (Aslan *et al.* 2009), long retention times are required (Aslan *et al.* 2009), and process failures can occur due to poor settling by oil-microbe agglomerates, the formation of pin-point flocs and/or overgrowth of filamentous species (Reddy *et al.* 2003; Chipasa & Mędrzyca 2006).

Anaerobic digestion is generally deemed unsuitable for the treatment of wastewater with high fat and/or oil content because of mass transfer limitations and inhibition of the functional microbial consortia caused by the presence of excess long and medium chain fatty acids (e.g. Chipasa & Mędrzyca 2006; Valladão *et al.* 2011; Samarasiri *et al.* 2016). Indeed, potential reactor failure due to accumulation of fatty acids was demonstrated in 1.2 L mesophilic and thermophilic upflow anaerobic filters treating vegetable oil effluent when operated at organic loading rates of >5.7 g COD/day (Kalat & Yüceer 2017). Although promising COD removal rates were still achieved, results cannot be extrapolated to full scale, where it is more difficult to achieve optimal mixing of the reactor contents, mass transfer and diffusion rates, and release of gases (Lettinga *et al.* 2001).

Aerobic mesophilic and thermophilic treatment technologies have been researched and/or implemented for oily industrial wastewaters, including, oily petfood effluent (Kurian *et al.* 2005), swine wastewater (Juteau 2006), food processing wastewater (Chiang *et al.* 2001), and synthetic wastewater containing olive oil (Hung *et al.* 2009). In addition, a combined thermophilic anaerobic–aerobic system has been tested for treatment of palm oil mill effluent (POME), which is discharged at high temperatures of 80–90 °C (Chan *et al.* 2015). At this time, high temperature aerobic technologies have not been proposed in literature for the treatment of ESO effluent.

Provided the ESO effluent is pre-treated to reduce the OG concentration, the CAS process can be efficient, and is widely used in industry (Azbar & Yonar 2004). Some of the organic fraction can be removed by simple gravity separation or dissolved air flotation (DAF) alone, but emulsified oils remain in the effluent: Pintor *et al.* (2014) achieved 91–99% removal of COD (11 ± 4 g/L) and 58–90% removal of OG (3.0 ± 1.0 g/L) using gravity separation, while Saatchi

Table 2 | Literature values for the most important parameters to measure in raw general process water and acid effluent from the edible seed oil industry (values are averages, ranges in brackets)

Process	Country	Oil	pH	COD _t (gO ₂ /L)	COD _s (gO ₂ /L)	BOD:COD _t ratio	OG (g/L)	COD _t :OG ratio	TP (mg/L)	SO ₄ ²⁻ (g/L)	TSS (g/L)	References
<i>Raw general process wastewater (may contain acid wastewater)</i>												
E, R	SA	Seed	(1.8–10.5)	4.6 (1.1–9.0)	–	–	0.6 (0.1–1.4)	7.3	–	1.8 (0.1–11.0)	–	Steffan <i>et al.</i> (1989)
CR, PR, V	Poland	Seed, palm*	(6.0–7.0)	1.2 ± 0.4 (1.0–1.7)	–	–	–	–	590 ± 94 (455–702)	16.6 ± 4.8 (11.0–20.6)	0.8 ± 2.6 (0.5–1.2)	Chipasa (2001)
–	Turkey	S/flower	(7.4–9.6)	9.4 (5.6–15.3)	–	0.6	3.0 (0.5–7.6)	3.1	379 (216–556)	0.6 (0.2–1.1)	7.8 (3.7–12.8)	Saatchi <i>et al.</i> (2001)
CR, V	India	Seed, palm*	2.3	29.1 ± 4.5	–	–	7.8 ± 0.2	3.8	57.4 ± 4	2.0 ± 0.2	7.9 ± 0.2	Pandey <i>et al.</i> (2003)
E, CR	Turkey	Seed	(6.3–7.2)	(13.8–15.0)	(6.5–7.0)	0.31	(3.6–3.9)	–	(61–63)	NG	(3.8–4.1)	Azbar & Yonar (2004)
R	Turkey	S/flower	(3.5–4.5)	9.2 ± 0.8 (8.3–9.7)	5.4 ± 0.2 (5.2–5.6)	0.2 0.3 (s)	0.7 ± 0.1 (0.5–0.8)	13.9	177 ± 210 (52–420)	11.4 ± 0.5 (10.8–11.7)	1.7 ± 0.2 (1.5–2.0)	Aslan <i>et al.</i> (2009)
R	Turkey	Corn	(2.7–2.8)	12.9 ± 2.2 (11.5–15.4)	5.7 ± 0.9 (5.1–6.7)	0.2 0.2 (s)	0.4 ± 0.1 (0.3–0.5)	34.4	583 ± 270 (275–775)	12.0 ± 0.5 (11.9–12.3)	2.9 ± 1.0 (1.1–3.0)	Aslan <i>et al.</i> (2009)
R	Portugal	S/flower	6.3	4.1 ± 0.4	–	1.0	0.7 ± 0.3	5.8	900 ± 200	3.4 ± 0.1	2.4 ± 0.3	Pintor <i>et al.</i> (2014)
E, CR	SA	Soya, S/flower	(8.8–11.6)	6.2 (0.9–11.7)	–	–	5.5	1.1	88 ± 61 (6–152)	0.3 ± 0.3 (0.02–0.8)	0.8 ± 0.5 (0.2–1.3)	Welz <i>et al.</i> (2017)
<i>Acid wastewater</i>												
CR, PR, V	Poland	Seed, palm	(2.5–6.0)	5.8 ± 2.0 (3.3–8.0)	–	–	–	–	5,694 ± 1,371 (4,599–6,982)	1.6 ± 0.5 (1.1–2.3)	4.0 ± 1.3 (2.5–5.4)	Chipasa (2001)
NG	SA	S/flower	–	251.5 ± 98.6 (152.8–350.0)	–	–	201.4 ± 79.7 (122.2–281.5)	1.2	–	–	15.1 ± 14.3 (0.7–29.3)	Roux-van der Merwe <i>et al.</i> (2005)
R	Portugal	S/flower	1.6	11 ± 4	–	0.5	3.0 ± 1.0	3.6	400 ± 200	0.2 ± 0.1	8.9 ± 0.5	Pintor <i>et al.</i> (2014)
E, CR	SA	Soya, S/flower	(1.8–5.8)	4.4 ± 3.3 (0.2–8.5)	–	–	1.6	2.8	402 ± 356 (186–602)	4.0 ± 4.0 (0.04–9.3)	1.6 ± 5.4 (0.2–6.1)	Welz <i>et al.</i> (2017)

E = expelling/extraction R = refining (not specified) CR = chemical refining PR = physical refining V = value added processes (e.g. margarine) COD_t = total COD COD_s = soluble COD BOD = biological oxygen demand BOD:COD_t = total BOD:COD OG = oil and grease TP = total phosphate TSS = total suspended solids Seed = seed type not stipulated S/flower = sunflower *palm (fruit) oil refined as well.

Table 3 | Performance of conventional full scale plants and laboratory studies for the treatment of edible seed oil effluent

Process	Scale	Organics				Inorganics		References
		COD _t		OG		TP		
		Influent (g/L)	Removal (%)	Influent (g/L)	Removal (%)	Influent (mg/L)	Removal (%)	
CC, DAF, ASP	Full-scale	13.7–15.0	92–96	3.6–3.9	93–95	61–63	97	Azbar & Yonar (2004)
CC, DAF, ASP	Full-scale	11.3	99	7.7	99	–	–	Abdel-Gawad & Abdel-Shafy (2002)
CC/floc, DAF	Full-scale	2.1–3.6	37–83	–	–	306–401	96–98	Chipasa (2001)
CC, ASP	Full-scale	24.6 ± 4.2	99.8	1.15 ± 0.1	>99	25.6 ± 0.01	39	Pandey <i>et al.</i> (2003)
SMBR	Lab 31 L	1.6 ± 0.1	86 ± 2	5.3 ± 0.7	95 ± 2	–	–	Ma <i>et al.</i> (2015)
ASP	Lab 3 L	1.5	84	–	–	–	–	Aslan <i>et al.</i> (2009)
ASP	Lab 3 L	1.8	92	–	–	–	–	Aslan <i>et al.</i> (2009)
Gravity separation	Lab 1 L	4.1 ± 0.4	91	0.7 ± 0.3	58	–	–	Pintor <i>et al.</i> (2014)
Gravity separation	Lab 1 L	11 ± 4	99	3.0 ± 1.0	90	–	–	Pintor <i>et al.</i> (2014)
EC	Lab 0.3 L	15.0	99	–	–	–	–	Un <i>et al.</i> (2009)
EC, E-ox.	Lab 1 L	8.8	99	–	–	–	–	Sharma & Simsek (2019)
Fenton oxidation	Lab 0.3 L	1.5	90	–	–	108	99	Barbusiński & Fajkis (2011)
Microfiltration	Lab 3 L	0.5–18.0	67	–	–	–	–	Šereš <i>et al.</i> (2016)
Reverse osmosis	Lab 30 L	2.5	99	<0.05	–	–	–	Shridar <i>et al.</i> (2002)
Biosorption	Lab jar	7.4	76	–	–	–	–	Dkhissi <i>et al.</i> (2018)
UAF	Lab 1.2 L	17.9–24.8	~88–99*	1.8–5.1	~53–99	–	–	Kalat D.G. Yüceer A. (2017)

ASP = activated sludge process, DAF = dissolved air flotation, CC = chemical coagulation, EC = electrocoagulation, E-ox = electrooxidation, floc = flocculation. SMBR = submerged membrane bioreactor, UAF = upflow anaerobic filter *extrapolated.

et al. (2001) obtained 17–69% removal of COD (9,350 mg/L (average), 5,600–15,300 mg/L (range)) and 29–83% removal of OG (3,030 mg/L (average), 540–7,640 mg/L (range)) using DAF.

Conventional technology consists of a combination of primary physicochemical and secondary biological processes that are mostly effective in removing COD, OG, SO_4^{2-} and TP (Table 2). This is accomplished by chemical coagulation or coagulation–flocculation with, for example, aluminium sulfate $[\text{Al}_2(\text{SO}_4)_3]$ or aluminium chloride $[\text{AlCl}_3]$ and poly ammonium chloride (PAC), followed by dissolved air flotation (DAF) (Chipasa 2001; Saatchi *et al.* 2001; Abdel-Gawad & Abdel-Shafy 2002; Pandey *et al.* 2003; Azbar & Yonar 2004). The CAS is still the secondary treatment of choice (Chipasa 2001; Abdel-Gawad & Abdel-Shafy 2002; Pandey *et al.* 2003; Azbar & Yonar 2004; Aslan *et al.* 2009).

The major problems with the conventional approach are that large volumes of chemicals are required, and copious amounts of potentially hazardous sludges are generated,

which require specialized disposal; secondly, macronutrients are removed during the physicochemical process, and these may require replenishing in order to meet downstream carbon:nitrogen:phosphorus (C:N:P) ratio requirements for the CAS (Saatchi *et al.* 2001; Pandey *et al.* 2003; Reddy *et al.* 2003; Azbar & Yonar 2004; Un *et al.* 2009; Pintor *et al.* 2014; Sharma & Simsek 2019). Dkhissi *et al.* (2018) proposed the use of 10% cactus (*Opuntia ficus indica*) as bioflocculant instead of chemical coagulation. While this approach has merit from an environmental perspective, factors such as feedstock availability, cost of feedstock transport and preparation, shelf-life, and downstream processing, among others, are needed in order to assess ‘real-world’ feasibility of bioflocculants.

In order to reduce the amount of sludge, membrane technologies, electrocoagulation, and oxidation technologies have been explored for COD and OG reduction in laboratory experiments (Table 2). Researchers have achieved good removal efficiencies with hollow-fibre polyvinylidene membranes (0.1 mm pore) in a submerged membrane bioreactor

(SMBR) (Ma *et al.* 2015), 200 nm pore size ceramic (aluminium oxide) microfiltration (MF) membranes operated with cross-flow (Šereš *et al.* 2016), and polyamide reverse osmosis (RO) membranes (Sridhar *et al.* 2002). The benefit of RO is that the water can be re-used in the process, an important factor to consider in water-scarce countries (Sridhar *et al.* 2002). However, for RO, the effluent needed to be pre-coagulated and pre-filtered, negating any perceived sludge-reduction benefits (Sridhar *et al.* 2002), while for MF the effluent needed to be pre-skimmed and filtered to remove particles >1 mm (Šereš *et al.* 2016). In the SMBR and MF systems, significant fouling occurred, which could only be removed by regular chemical cleaning of the membranes (Ma *et al.* 2015; Šereš *et al.* 2016), and the MF system required heating to 60 °C to maximize efficiency (Šereš *et al.* 2016). These studies suggest that membrane technologies do not offer better treatment options than conventional technologies at this point in time because of the high capex, operational costs, and in some instances, the environmental burden from ancillary waste streams.

Some research has been conducted on more advanced technologies for ESO wastewater treatment, including, electrocoagulation, electrooxidation and Fenton's oxidation. Electrocoagulation reduces the amount of sludge produced by removing suspended and colloidal particles, but cannot remove the soluble COD fraction, and is reliant on electrical energy (Un *et al.* 2009; Sharma & Simsek 2019). Un *et al.* (2009) managed to reduce electricity consumption from 131 to 42 kWh per kgCOD_{removed} using Al sacrificial electrodes when PAC was added as a coagulant and sodium sulfate (Na₂SO₄) as a support electrolyte in small-scale (0.3 L) and pH-controlled reactors (pH = 7), and Sharma & Simsek (2019) increased the removal of soluble COD from 75% to 99% by combining electrocoagulation with electro-oxidation. The optimal use of Fenton reagent followed by precipitation with NaOH or calcium oxide (CaO) has been shown to effectively remove COD and TP from ESO, but has the same problem with sludge generation as conventional coagulation (Barbusiński & Fajkis 2011). This could possibly be overcome by utilizing a solid catalyst and/or photo-Fenton (Domingues *et al.* 2018). Some of these advanced technologies are promising and merit scale-up and techno-economic assessments, including environmental parameters.

Little has been reported in literature on valorization of ESO effluent. Roux-van der Merwe *et al.* (2005), showed that various strains of fungi isolated from soil were able to reduce the COD of acid ESO wastewater supplemented with N. The highest reductions were achieved by *Cunninghamella echinulata* and *Aspergillus fumigatus* (98.2% and 97.8%,

respectively) when grown at 30 °C for 7 days. Similarly, Yu *et al.* (2018) showed that the oleaginous yeast, *Trichosporon fermentans*, was able to reduce the COD of refined soybean oil effluent by 94.7% within 40 h without the need for nutrient addition. Roux-van der Merwe *et al.* (2005) showed that some fungal strains were able to accumulate high fractions of gamma-linoleic acid (GLA), a valuable nutraceutical, in their biomass (maximum 45% (w/w) by *Emericella nidulans* with concurrent 95.3% COD reduction), and Yu *et al.* (2018), showed that their strain of *T. fermentans* was able to convert saturated to unsaturated fatty acids and accumulated 43% (w/w) oil in biomass under optimized conditions. The accumulated oils exhibited a favourable fatty acid profile for biodiesel production. Such biotechnologies that are able to achieve effluent remediation with concurrent production of valuable products feed into the global move toward circular economies and merit further pilot-scale research followed by techno-economic assessments.

Valorization of wastewater sludge

Wastewater sludge from the ESO industry is an indirect form of solid waste that is generally sent to landfill (Chipasa 2001; Welz *et al.* 2017). Pandey *et al.* (2003) characterized clarifier sludge from the CAS process at an ESO processing site. They found that the sludge contained 76% organic matter and a favourable nutrient content for composting as a low value product, but one that allowed the sludge to be directed away from landfill at this site. This is simple to institute and should be considered at other sites.

This clarifier sludge has also been shown to contain a large fraction of oil that is suitable for the production of second generation biofuel (Ngoie *et al.* 2019a, 2019b; Muanruksa & Kaewkannetra 2020). Although production of most next generation biofuels is currently not economically viable, it is only a matter of time until they gain traction as countries move towards circular economies and production technologies improve (Corea *et al.* 2019; Corona *et al.* 2019). Biodiesel generated from waste cooking oil is already being widely used, and a wealth of research manuscripts and reviews (e.g. Awogbeni *et al.* 2019; Moazeni *et al.* 2019; Tan *et al.* 2019) have been dedicated to evaluations of production processes and biodiesel quality assessments.

CONCLUSION

In line with the move to circular economies, waste from the edible oil industry has great potential for further valorization

and water re-use. In order to provide realistic industry benchmarks, it is imperative that qualitative and quantitative water use and waste generation data are collected and collated.

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