Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.838526

53 (2015) 309–318
January

Taylor & Francis
Taylor & Francis Group

A review on sugar industry wastewater: sources, treatment technologies, and reuse

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Received 13 June 2013; Accepted 20 August 2013

ABSTRACT

Sugar industries have an important place in the Indian economic development. However, the wastewater generated from these industries bear a high degree of pollution load. Sugar industries in India generate about 1,000 L of wastewater for one ton of sugar cane crushed. Wastewater from sugar industry, if discharged without treatment, poses pollution problems in both aquatic and terrestrial ecosystems. In this review, the sugar industry wastewater generation sources, characteristics, recent advancements in the aerobic, anaerobic, and physico-chemical treatment technologies, and the areas needing further research have been explored. Possibility of treated wastewater reuse was also investigated. Most of the research work for sugar industry wastewater treatments has been carried out by anaerobic treatment processes. However, oil and grease are not easily degraded by anaerobic processes. Also, an anaerobic process partly degrades nutrients whereas, aerobic processes consume higher energy. Anaerobic-aerobic combined systems can remove organics completely. Unfortunately, very few studies are available for anaerobic-aerobic combined systems, and more work is needed in this field.

Keywords: Sugar industry; Wastewater sources and characteristics; Aerobic treatment; Anaerobic treatment; Physico-chemical treatment

1. Introduction

India is the world's largest sugar-consuming country and the second largest in terms of sugar production. The growth of sugar factories along with the sugar industries segment depicts the sugar industry scenario in India [1]. Cane cultivation areas increased to 5,086,000 hectares in 2011–2012, which were 5,055,000 hectares in 2007–2008. Moreover, there were 516 industries in operation in 2007–2008. Currently, in 2011–2012, this figure increased to 529, producing 26.0 million tons of sugar [2]. Consequently, the amount of wastewater generated from these industries has also increased.

Sugar industries wastewaters are characterized by high biological oxygen demand (BOD), chemical oxygen demand (COD), and total dissolve solids. Wastewater from sugar industry generally contains carbohydrates, nutrients, oil and grease, chlorides, sulfates, and heavy metals [3–6].

The sugar industries have important place in the Indian economic development. However, the wastewater generated from these industries bears high degree of pollution load. Wastewater from sugar industry, if discharged without treatment, poses pollution problem in both aquatic and terrestrial ecosystems [7]. Also, sugar industry wastewater when not treated completely produces unpleasant smell when released into the environment. Moreover, Indian government imposed very strict rules and regulations for the effluent discharge to protect the environment (Table 1). Therefore, suitable treatment methods are required to meet the effluent discharge standards.

Primary treatment of sugar industry wastewater includes filtration, sedimentation, and load equalization [8,9]. Whereas, secondary treatments are biological methods like lagoons [10–12], aerated ponds [10], up-flow anaerobic sludge blanket (UASB), expanded granular sludge blanket, fluidized bed reactor (FBR) [13,5]. Sometimes combined anaerobic and aerobic treatments are also used for sugar industry wastewater treatment [10,14].

In this review, the sugar industry wastewater generation sources, their characteristics, recent advancements in the aerobic, anaerobic, and physicochemical treatment technologies, and the areas in which further research is needed have been identified. Possibility of treated wastewater reuse was also investigated.

2. Process, wastewater sources, and characteristics

Processing steps involved in production of sugar are milling, clarification, evaporation, crystallization, and centrifugation. In milling process, sugar cane is crushed to extract juice. During milling process, some amount of water is added to crushing cane, known as imbibition water, to increase the efficiency of juice extraction [15]. After extraction of juice, fibrous residue, which is known as bagasse, is generally utilized as fuel for boiler after drying. The extracted juice is very turbid and greenish in color, which is then clarified and bleached with $Ca(OH)_2$ and SO_2 dosing followed with clarification by continuous clarifier. The clear juice is decanted, and thickened sludge is send to the rotary drum vacuum filter for the recovery of remaining juice contained in sludge. Here, in this filtration process, water is added to enhance the efficiency of process, and the dewatered sludge known as press mud is discarded and utilized as fertilizer. The clear juice is then send to vacuum multiple-effect evaporators, where juice is concentrated. Afterwards, sucrose crystallization is carried out using pans where the remaining water is evaporated under vacuum. Product leaving the vacuum pans is called massecuite, which is then centrifuged, washed, dried, screened, and packaged [16].

In view of generated wastewater volume and characteristics, sugar industries are one of the most polluting industries. Volume of effluent generated depends on the cane crushing capacity of industry and management of water [16]. Sugar industries in India generate about 1,000 L of wastewater for one ton of sugar cane processed [17]. Therefore, the sugar industry having the capacity of 2,500 tons crushed per day (TCD) will generate about 450×10^6 L of wastewater in a running session of six months. It has also been reported that Mexican sugar industries generates $45.9\,m^3/s$ wastewater ($713.83 \times 10^6\,m^3$) for six months running session [18].

Sugar industry wastewaters are produced mainly by cleaning operations. Washing of milling house floor, various division of boiling house like evaporators, clarifiers, vacuum pans, centrifugation, etc. generates huge volume of wastewater. Also, wash water used for filter cloth of rotary vacuum filter and periodical cleaning of lime water and SO_2 producing house becomes a part of wastewater. Periodical cleaning of heat exchangers and evaporators with NaOH and HCl to remove the scales on the tube surface

Table 1
Minimal standards for discharge of effluents from the sugar industry

Parameter	Maximum value (mg/L)	
	World bank guidline[a]	CPCB, India[b]
pH	6–9	–
BOD_3	–	100 for disposal on land, 30 for disposal in surface water
COD	150–250	–
Total suspended solids	50	100 for disposal on land, 30 for disposal in surface water
Oil and grease	10	10
Total nitrogen	–	–
Total phosphorus	–	–
Temperature	$\leqslant$3°C increase	–

[a]World Bank [8]. [b]http://cpcb.nic.in/Industry-Specific-Standards/Effluent/411.pdf

Table 2
Characteristics of sugar industry wastewaters (composition in mg/L, except for pH)

Waste type	COD	BOD_5	pH	TS	VSS	TKN	TP	Ca	Cl	References
BSI	6,621 ± 113	–	7	6,062 ± 53	335 ± 7	10	3	–	48–559	[23]
CSI	8,339–9,033	4,641–5,103	7	–	–	–	–	–	–	[27]
SBS	6,300	–	–	–	–	53 (TN)	5	906	–	[5]
BSI	6,513	3,837	8	763 (SS)	–	44 (TN)	3	441	1,043	[61]
SR	2,731	–	–	–	–	4 (NH_4^+), 6 (NO_3^-)	–	100	195	[62]
CSI[a]	110–3,400	60–1820	6–10	5–1,480 (TSS)	–	–	–	–	–	[19]
CSI[b]	7,568	3,163	4.5	1,769 (TSS)	654	38	12	–	–	[22]
BSI	3,382	–	8	–	–	–	–	–	–	[63]
CSI	1,000–4,340	350–2,750	5–6.5	760–800 (TSS)	173–2,190	15–40	1–3 (P)	–	–	[17]
CSI	12,211	3,131	9.5	9,212 (TSS)	–	–	–	2,460 ($CaCO_3$)	3,195	[20]

BSI: beet sugar industry; CSI: cane sugar industry; SBS: synthetic beet sugar wastewater; SR: sugar refinery. [a]oil = 23 mg/L; [b]oil and grease = 118 mg/L.

contributes organic and inorganic pollutant loadings to wastewater. Leakages from pumps, pipelines, centrifuging house also contribute to wastewater produced. Except this, wastewater is also produced from boiler blowdown, spray pond overflow [19], and from condenser cooling water which is discharged as wastewater when it gets contaminated with cane juice.

Sugar industry wastewater contains wash water with lost cane juice in various operations, detergents, bagasse particles, oil and grease used for lubrication, and lost sugar solids in process. It is characterized by high concentrations of nutrients, organic and inorganic contents [20]. Ahmad and Mahmoud [21] have nicely reported the characteristics of wastewater from six different sugar industries. Quantity and composition of sugar industry wastewater depend on the final products, production processes, equipments used, and composition variations [22]. Table 2 shows characteristics of sugar industry wastewater reported by various authors. It can be seen that there is large variation in COD (110–12,211.44 mg/L) and BOD (60–5,103 mg/L) (Table 2). Most of the COD loading to wastewater is due to the lost cane juice and sugar solids. The pH and total solids (TS) concentration varies in the range of 4.5–10 and 6,062 ± 62 mg/L, respectively [23]; and significant amount of nutrients, 15–40 mg/L of total Kjeldahl nitrogen (TKN) [17] and 1.3–12 mg/L of total phosphorous are also found in sugar industry wastewater. Except this, very high amount of chlorides (48–3,195 mg/L), ca ($CaCO_3$), SO_4^+, Na^+, K^+, and heavy metals (Zn^{2+}, Ni^{2+}, Cu^{2+}, Mn^{2+}, Pb^{2+}, Cd^{2+}, Cr^{3+}, and Fe^{2+}) [20] have also been reported in literature.

3. Treatment methods

Screening, grit removal, flow equalization, sedimentation, or dissolved air flotation are used to reduce suspended solids (SS) load from sugar industry wastewater. Biological treatment methods are applied for the reduction of soluble organic matter and disinfections [22]. Biological treatment includes aerobic and anaerobic process. Except biological methods, physico-chemical methods are also used for sugar industry wastewater treatment.

3.1. Biological methods

Since, sugar industry wastewater contains mostly sugars and volatile fatty acids, which are easily biodegradable, therefore all the biological (anaerobic and aerobic) treatment processes are suitable [22]. Table 3 summarizes the reported literature of biological treatment for sugar industry wastewater treatment.

3.1.1. Anaerobic treatment

Anaerobic treatment method for concentrated wastewater, in terms of pollutants (as the sugar industry wastewater), is widely used method in the industries. It has several advantages over aerobic processes, which include the lesser energy required; methane production due to the degradation of organic matters, which is a source of energy; and lesser sludge production, which indirectly reduces sludge disposal costs greatly [24–26]. Anaerobic batch reactor, anaerobic fixed-bed reactors (AFR), up-flow anaerobic fixed bed (UAFB) reactor, and UASB reactor are generally used for anaerobic treatment of sugar industry wastewater (Table 3).

Anaerobic and facultative lagoons have been previously used for years. However, lower removal efficiency and larger area requirement are the drawbacks of this method [27]. Sanchez Hernnandez and Travieso Cordoba [28] reported the application of AFR to treat sugar-mill wastewater with varying hydraulic retention times (HRT) (0.5, 1.0, 2.0, and 4.0 d). It was found that the increase in HRT increased organic matter removal and more than 90% of COD removal was found at 4 d HRT.

Most of the sugar industries have implemented only solid separation pretreatment with clarifiers/dissolved flotation systems [22]. Effluent discharged from these industries needs further treatment to avoid adverse environmental effects in the water receiving bodies. Some mills utilize this treated wastewater for irrigation purpose, but clogging problems arise when the solids are not removed completely. Moreover, Doke et al. [29] have reported that the plant growth and crop yield are reduced, and soil health is affected, if irrigated with wastewater treated by this method. Therefore, complete removal of pollutants is necessary. In this regard, the mesophilic UASB reactor was studied and evaluated by Nacheva et al. [22] for the treatment of previously treated sugar cane mill wastewater. They reported more than 90% COD removal at organic loading rate (OLR) up to 16 kg COD/m^3 d with high biogas production. Finally, they concluded that the discharge standards in terms of COD concentration can be found if the UASB reactor is operated at lower OLR of 4 kg COD/m^3 d; but at higher OLR, an additional biological treatment stage is needed. Hampannavar and Shivayogimath [17] have also reported sugar industry wastewater treatment in a UASB reactor seeded with a non-granular anaerobically digested sewage sludge, operated with OLR of 0.5–16 kg COD/m^3 d. Optimum HRT was found to be 6 h giving maximum COD removal efficiency of 89.4%. In another study [30], treatment of strong sugar-beet wastewater by an UAFB was done, and it was reported that the COD removal efficiencies $\geqslant$90% could be achieved. They have also reported that by using a suitable packing material, the system is capable of tolerating very high organic loading of 10 kg COD/m^3 d. Jayanthi and Sonil [31] investigated the effectiveness of *Cyanobacteria* for the bioremediation of sugar industry effluent. It was reported that the color, BOD, COD, and TDS removal were found to be 39.2, 25.69, 37.9,1 and 48.51%, respectively, in four weeks of treatment.

Waste characteristics, reactor configurations, and operational parameters all affect the efficiency of anaerobic digestion [32]. If the waste characteristics are unsuitable for anaerobic treatment, co-digestion is

Table 3
Reported studies on biological treatment methods for sugar industry wastewaters

Waste type	Reactor type	% COD reduction	BOD/COD loading	HRT	Methane yield (mL/g $COD_{removed}$)	References
BSI and BP	Anaerobic batch reactor[a]	64–87	–	–	236–322	[31]
CSI	AFR	<90	–	4 (d)	–	[27]
SR	Rotating biological contactor[b]	48	–	–	–	[38]
CSI	aerated fixed-film biological systems[c]	74–68%	0.005–0.120 kg BOD / m^3 d	2–8 (h)	–	[47]
CSI	UASB	>90	16 kg COD m^{-3} d^{-1}	–	$355 \times 10^3 \pm 2 \times 10^3$	[22]
BSI	UAFB	>90	10 kg COD m^{-3} d^{-1}	20 h	–	[35]
CSI	UASB	89%	16 kg COD m^{-3} d^{-1}	6 h	–	[17]

[a]F/M range (0.51–2.56 g COD/g VSS and 70–89% VS reduction. [b]Phenol reduction = 63% and color reduction = 55%. [c]COD removal efficiency = 98–89%.

one of the alternate used to enhancement the anaerobic degradation of wastes with different characteristics. Alkaya and Demirer [32] used sugar-beet industry wastewater and exhausted beet pulp was subjected as a co-digestion system for anaerobic biodegradation in batch reactors. About 63.7–87.3% of COD and 69.6–89.3% of volatile suspended solids (VSS) removal were observed for 0.51–2.56 g COD/g VSS F/M range. This shows high biodegradability for both wastewater and beet pulp. Alkaya and Demirer [33] conducted experiments for the treatment of sugar-beet processing wastewater and beet pulp simultaneously. The waste was first treated in a batch-fed continuously mixed anaerobic reactor (FCMR), then the same reactor was used as an anaerobic sequential batch reactor (SBR), and the performance was compared with the methane production. It was reported that the methane production yield was increased to 32.2% when the configuration was changed from FCMR to anaerobic SBR. In an another study, Samaraweera et al. [34] studied on anaerobic treatment for sugar industry wastewater and reported that chlorination, addition of macronutrient, and increase in temperature improved the process in terms of filaments and lipopolysaccharide disappearance from the anaerobic tank, decrease in concentration of the anaerobic clarifier overflow solids, increase in the concentration of the anaerobic clarifier underflow solids, increase in alkalinity in the anaerobic tank, decrease in total volatile fatty acids in the anaerobic tank, increase in percent methane in the biogas, and increase in COD loading.

Various steps involved in organic pollutants degradation by anaerobic process are hydrolysis/fermentation, acetogenesis, and methanogenesis; and anaerobes involved are fermentative bacteria, acetogenic bacteria, and methanogens, respectively [35,30]. Alkaya and Demirer [23] studied for maximizing the hydrolysis and acidification of sugar-beet processing wastewater and beet pulp to produce volatile fatty acid using acidogenic anaerobic metabolism in continuously mixed anaerobic reactors. The important step in this is to inhibit the methanogenic activity. Optimum HRT of 2 d with 1:1 waste mixing ratio (in terms of COD) showed highest total volatile fatty acid concentration $3,635 \pm 209$ mg/L as acetic acid with the acidification degree of $46.9 \pm 2.1\%$. Bacterial immobilization on solid supports leads to better cell–liquid separation and enables the system to hold high count of active biomass in the reaction system during the anaerobic treatment [36,37]. Jördening et al. [13] investigated a system for hydolysis/acidification of sucrose-containing wastewater with the immobilized bacteria on solid supports. For organics hydrolysis and denitrification process, FBRs were used and nitrification was studied in an airlift reactor system for sugar industry wastewater. It was concluded that the porous materials retain higher quantity of biomass for the hydrolysis (up to 55 kg/m^3). During nitrification, pumice used as support material showed best result with 1.2 kg NH_4–N/(m^3 d) of nitrification; and the denitrification rate was found to be four times higher (3.5–5 kg NO_3–N/(m^3 d)). In an another study, *Phanerochaete chrysosporium* immobilized on polyurethane foam and scouring web decolourized efficiently the sugar refinery effluent in a long-term repeated batch operation. It was found that the color, total phenols, and COD were reduced by 55, 63, and 48%, respectively [38].

3.1.2. Aerobic treatment

Aerobic biological treatment generally involves degradation of organics in the occurrence of oxygen. Conventional aerobic treatment includes activated sludge, trickling filters, aerated lagoons, or a combination of these [39]. Sugar industry wastewaters are biodegradable except oil and grease which are not easily degraded by anaerobic processes [40], because oils produce long-chain fatty acids during the hydrolysis step which causes retardation in methane production [41]. Long-chain fatty acids were reported to be inhibitory to methanogenic bacteria [42].

Ahmad and Mahmoud [21] conducted experiments in batch reactor to show whether the aerobic treatment for sugar industry wastewater is acceptable. It was reported that the aerobic biodegradation of wastewater is agreeable. It was also reported that the COD reduction can be predicted at given parameters with the help of relationship suggested by Tucek et al. [43].

Earlier, lagoons were used for sugar industry wastewater treatment [44,10] because of being an economic process. But, larger area requirements [10] and emission of unpleasant and annoying odor during the treatment process [45] are some of the disadvantages of lagoons. Aerated lagoons were also used in past, and showed lesser residence time and area required compared to lagoons, to treat sugar industry wastewater, but oxygen consumption and HRT were found to be high, and still large area requirement is disadvantage [10]. Effluents from Mumias Sugar factory is treated using ponds before discharging into Nzoia River. To explore the pollution of river due to this activity, Moses' et al. [46] examined the samples for temperature, pH, BOD, COD, TDS, and TSS and concluded that the values were well above than discharge limits defined by NEMA and the World Health Organisation (WHO). Hamoda and Al-Sharekh [47] examined the performance of a system, aerated submerged fixed-film (ASFF), in which bio-film was attached on submerged ceramic tiles with diffused aeration condition. It was concluded that the ASFF process is capable of handling severe organic loadings of 5–120 g BOD/m^2 d with minute decrease from 97.9 to 88.5% in BOD removal efficiency and from 73.6 to 67.8% in COD removal efficiency. Nitrification rate was also decreased but at higher rates.

None of the above studies showed completely/nearly complete organics removal. Therefore, an additional biological treatment stage is needed. Hybrid systems of comprising anaerobic and aerobic treatments have been approved capable of giving high COD removal efficiency with smaller required energy [5,10,14]. Yang et al. [48] reported a combined anaerobic (UASB) and aerobic (EAFB) treatment system for effluent from primary treatment of sugarcane mill wastewater for its application for drip irrigation, and ⩾99% organics and solids removal were reported at HRT of 2 d. This treated wastewater hold better water quality for drip irrigation.

3.2. Physico-chemical methods

Coagulation/flocculation with inorganic coagulants and adsorption are widely used for the removal of suspended, colloidal, and dissolved solids (DS) from wastewaters. Generally, coagulation/flocculation is used in the primary purification of industrial wastewater (in some cases as secondary and tertiary treatment) [40]. In coagulation process, insoluble particles and/or dissolved organic materials aggregate to be larger, and are removed by sedimentation/filtration stages.

Only one study is reported in open literature by coagulation with lime and subsequent adsorption with activated charcoal [20]. BOD and COD removal efficiency was reported to be 96 and 95%, respectively. Parande et al. [49] studied on COD removal from sugar industry wastewater using metakaolin, tamarind nut carbon, and dates nut carbon as adsorbents. Langmuir and Freundlich adsorption isotherms were reported to fit the experimental data. Studies revealed that metakaolin was found to give maximum COD removal efficiency at a dosage of 500 mg/L in a contact time of 180 min at pH = 7.

Electro-chemical (EC) treatment process is an emerging wastewater treatment technology. EC treatment method involves electro-oxidation, electro-coagulation, and electro-floatation. In electro-oxidation (EO) treatment, organic materials are oxidized to carbon dioxide and water or other oxides by electrochemically generated reactive oxygen and/or oxidizing agent. Whereas, electro-coagulation process involves generation of anode material hydroxides and/or poly hydroxides which remove the organics by coagulation. Electro-flotation process removes pollutants with the help of buoyant gases bubbles generated during electrolysis, which take with them the pollutant materials to the surface of liquid body [50].

Capunitan et al. [51] investigated electro-oxidation and electro-coagulation to treat spent ion-exchange-process wastewater from a sugar refinery at different current values. EO method showed 99.9, 63.1, and 90.5% of decolorization, COD removal, and TSS removal, respectively, at 5 A in 7 h electrolysis time. Whereas, in electro-coagulation 71.2, 18.5, and 97.4% of decolorization, COD removal, and TSS removal were found, respectively, at 5 A in 8 h electrolysis time. EO was concluded as the better treatment option in comparison to electro-coagulation not only in terms of removal, but also in terms of energy cost.

In another study, Guven et al. [5] conducted EC experiments to treat simulated sugar-beet factory wastewater. The effect of various operational variables such as applied voltage, electrolyte concentration, and waste concentration was studied for percentage COD removal and initial COD removal rate. Highest COD removal and COD initial removal rate were reported as 86.36% and 43.65 mg/L min, respectively, after 8 h at the applied voltage of 12 V, 100% waste concentration with 50 g/L NaCl. At optimized set of process variables and at 100% waste concentration, percentage COD removal and COD initial removal rate were found to be 79.66% and 33.69 mg/L min, respectively. In EC process, the electrode material plays a very important role in quality of treatment. Asaithambi and Matheswaran [52] conducted EC experiments to treat simulated sugar industrial effluent with RuO_2-coated titanium as an anode and stainless steel as a cathode. Maximum percentage COD removal was reported to be 80.74% at 5 A/dm^2 current density and 5 g/L of electrolyte concentration in the batch electrochemical reactor.

4. Treated effluent quality, reuse and recommendations

Form the above study, it can be said that most of the research works for sugar industry wastewater treatment have been carried out by anaerobic treatment process. As discussed earlier in Section 3.1.2, oil and grease are not easily degraded by anaerobic processes [40] due to the production of long-chain fatty acids during hydrolysis step, which causes retardation in methane production. Also, anaerobic process partly degrades nutrients. Moreover, none of the study reports complete removal of organics (Table 3).

In the field of aerobic treatment process, aerated lagoons, ASFF culture, and mixed culture activated sludge process have been used for the treatment of sugar industry wastewater. However, future studies have to give attention on aerobic SBR treatment, which is mixed culture activated sludge process and not previously reported in literature. Various authors have reported previously the treatment of varieties of wastewater by aerobic SBR [53–59] and showed that aerobic SBR give high percentage of organics removal. Also, in the case of aerobic SBR, smaller area is needed as compared to other aerobic activated sludge processes.

Anaerobic-aerobic combined system can remove organics completely from sugar industry wastewater [48]. Very few studies are available for anaerobic-aerobic combined systems, and more work is needed in this field.

Because sugar industry wastewater bears high loading of DS and SS, physico-chemical methods like adsorption and coagulation are well suited for its treatment. However, only one study for coagulation followed by adsorption [20], and another study by Parande et al. [49], for adsorptive treatment of sugar industry wastewater, is reported. Moreover, in this study, mechanism of coagulation/adsorption is lacking.

Table 4
Opportunities and limitations of aerobic, anaerobic, and physico-chemical treatment methods for sugar industry wastewater

Treatment method	Opportunities	Limitations
Anaerobic	• Comparatively smaller reactor in size • Lesser energy is required • Energy production is possible due to generation of methane production during degradation of organic matters • Excess sludge produced is less • Up to 90% of VSS removal may be achieved with co-digestion [32] • Effluent quality in terms of COD is good [40] • High COD loading of 16 kg COD $m^{-3} d^{-1}$ is possible [17,22] • Nitrogen removal is low, however denitrification rate during treatment may be increased with immobilised bacteria on solid supports [13]	• Oil and grease are not easily degraded [40] • Anaerobic process partly degrades organics • Post-treatment of effluent is often required
Aerobic	• Aerated submerged fixed-film (ASFF) process is capable of handling severe organic loadings of 5–120 g BOD/m^2 d • Excellent effluent quality in terms of COD, BOD, and nutrient removal • Aerobic-SBR has been reported to give high percentage of organics removal for varieties of industrial wastewater [53–59]. Therefore, it may be a good option for the sugar industry wastewater treatment • Also, in the case of aerobic SBR smaller area is needed as compared to other aerobic activated sludge processes	• Excess sludge produced is high • Require larger area [10] • Emission of unpleasant and annoying odor during the treatment process [45] using lagoons • None of the studies available reports complete removal of organics • Aerobic SBR treatment systems are more controlling
Physico-chemical	• Coagulation/flocculation, adsorption and electro-chemical methods are the various physico-chemical methods reported for sugar industry wastewater treatment • Combined system of coagulation with adsorption has been reported to give BOD and COD removal efficiency of 96 and 95%, respectively [20] • Electro-oxidation was shown as the better treatment option in comparison to electro-coagulation [51] • No generation of secondary pollutants take place in electro-oxidation method	• Chemical coagulation/flocculation process generates secondary pollutants • In electro-coagulation process electrodes are dissolved into wastewater due to oxidation, and need to be regularly replaced • A layer of electrode material oxide is deposited over the cathode leading decrease in efficiency of electro-coagulation process • In the case of electro-coagulation, treated effluent may be contaminated with electrode material

Kinetic and isotherm parameters for adsorption process have not been reported, which are important for the design of any adsorption unit. More study with different types of electrodes is needed for the EC treatment of sugar industry wastewater. EO is an emerging area for wastewater treatment, needs to be explored for sugar industry wastewater. In EO process organic contamination are oxidised directly at the surface of the electrode or an oxidising agent is generated electrochemically. Therefore, no generation of secondary pollutants take place. Various opportunities and limitations of aerobic, anaerobic, and physico-chemical treatment methods for sugar industry wastewater are shown in Table 4.

Imbibition water, cooling water, boiler make-up water, scrubber feed and scrubber make-up water, and condenser feed and condenser make-up water are various water using streams in sugar industries. An average amount of approximately 11 m^3 of water is required in one day for these activities for one ton of cane crushed [19]. Therefore, daily 27,500 m^3 of water is needed for a sugar industry having capacity of 2,500 TCD. Treated wastewater may be reused for different water consuming activities in order to reduce fresh water load and to achieve the target of zero water discharge. On other hand, irrigation is one of the traditional utilization of treated wastewater from sugar industries. Due to residual pollutants in treated wastewater, it was reported that plant growth was affected and crop yield was reduced. Also, affected soil health has been reported [29].

Membrane assisted treatment such as reverse osmosis (RO), microfiltration (MF), nanofiltration (NF), ultrafiltration (UF) are very capable where there is need to produce high-quality effluent to reuse directly [40,60]. No work is reported in open literature for the treatment of sugar industry wastewater using membranes in best of author knowledge. But, sugar industry wastewater bears high load of DS and SS, this will lead to severe fouling of membranes. Therefore, in view of producing good quality treated wastewater for reuse, hybrid system comprising membranes with aerobic/anaerobic treatment methods and/or physico-chemical methods may be promising.

5. Conclusion

Although, generally the anaerobic process is used for the treatment of sugar industry wastewater, this method is limited due to the production of long-chain fatty acids during hydrolysis of oil and grease. Also, anaerobic processes do not completely remove nutrients/organics; therefore, anaerobically treated effluents need further treatment. Aerobic SBR may be the promising treatment technology for the sugar industry wastewater, because aerobic SBR has been reported to give good removal efficiency in terms of both nutrients and other organics.

Membrane-assisted treatment may be very effective where there is need to produce high-quality effluent to reuse. But, sugar industry wastewater bears high load of DS and SS, this will lead to severe fouling of membranes. Therefore, in view of producing good quality treated wastewater for reuse, hybrid system comprising membranes with aerobic/anaerobic treatment methods and/or physico-chemical methods may be promising.

Abbreviations

BOD — biological oxygen demand (mg/L)
COD — chemical oxygen demand (mg/L)
TCD — tones crushed per day
TS — total solids
TKN — total Kjeldahl nitrogen (mg/L)
AFR — anaerobic fixed-bed reactors
UASB — up-flow anaerobic sludge blanket
HRT — hydraulic retention time
OLR — organic loading rate
UAFB — up flow anaerobic fixed bed
TDS — total dissolved solids
VSS — volatile suspended solids
FCMR — batch-fed continuously mixed anaerobic reactor
SBR — sequential batch reactor
TSS — total suspended solids
ASFF — aerated submerged fixed-film
DS — dissolved solids
SS — suspended solids
NF — nanofiltration
RO — reverse osmosis
MF — microfiltration
UF — ultrafiltration
EC — electro-chemical
EO — electro-oxidation
TP — total phosphorous

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