Comprehensive review on wastewater discharged from the coal-related industries – characteristics and treatment strategies

Deblina Maiti, Iqbal Ansari, Mohd Ashraf Rather and Arukula Deepa

ABSTRACT

Wastewaters discharged from various coal-related activities deteriorate fresh water quality and inflict possibilities of groundwater contamination. Their characteristics mostly depend on the parent coal properties, though some of the pollutants are cyanide, thiocyanate, ammonia, phenol, heavy metals and suspended solids. This paper has reviewed the treatment techniques along with the characteristics of all such kinds of wastewater and also identified the challenges and future perspectives. Primarily, demineralization of coal can attenuate and control release of pollutants in wastewaters if implemented successfully. Mine water from non-lignite mines can be purified using simple techniques, for its reutilization. Acidic mine water and leachates can be treated using passive bioreactors with microbial activity, different organic substrates and limestone drains. Additionally bio-electrochemical systems, membranes, macrocapsules, zeolite filters, ores, physical barriers, and aquatic plants can also be used at various stages. Coal washery wastewater can be treated using natural coagulants obtained from plant extracts along with conventional coagulants. Nitrification and denitrification bacteria fixed in reactors along with activated carbon and zero-valent iron can treat coke oven wastewater. Some other sophisticated techniques are vacuum distillation, super critical oxidation, nanofiltration and reverse osmosis. Practical use of these methods, wisely in an integrated way, can reduce freshwater consumption.

Key words | acid mine drainage, coal washery, coke plant, leachate, microbes, mine water

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ABBREVIATIONS

A1-A2-O	Anaerobic–anoxic–aerobic biofilm system
ALD	Anoxic limestone drain
AMD	Acid mine drainage
BDD	Boron-doped diamond anode system
COD	Chemical oxygen demand
FA	Fly ash
MBR	Membrane bioreactor
MW	Mine water
NF	Nanofiltration
RO	Reverse osmosis
SRB	Sulphate reducing bacteria
TCN	Total cyanide
TN	Total nitrogen
TOC	Total organic carbon
TPP	Thermal power plant
WW	Wastewater
ZVI	Zerovalent iron

INTRODUCTION

Rapid increase in the usage of coal has resulted in release of coal-related toxic pollutants through wastewaters (WWs) originating from coal mining sites, washeries, coke plants, and thermal power plants (TPPs). The quality of these WWs depends on the coal properties and the process involved in coal processing. Discharge of these WWs gravely impacts the quality of nearby water bodies, aquatic life and the food chain along with the groundwater (Pal & Kumar 2014).

The above coal-related industries mainly release four kinds of WW. The first of is mine water (MW), which is generated in ample amounts during non-lignite coal mining. It is mostly affected by hardness, suspended solids and bacterial contaminants (Soni & Wolkersdorfer 2016). Comparatively, one other kind of MW also called acid mine drainage (AMD) originating from lignite mines is highly contaminated with metals. Oxidation of pyrite present in the mine overburden dumps in presence of moisture is the actual cause of AMD generation, which also dissolves many toxic metals such as zinc, copper, iron, manganese, cadmium, nickel, chromium, lead, cobalt, and mercury during its passage from the rocks (Equeenuddin *et al.* 2010). Seeping of the AMD into water systems leads to 2–1,200 times more metal concentration in them compared to the world average metal concentration in water bodies. The metals are non-biodegradable and some of them such as lead, cadmium, and mercury, are highly toxic to living organisms. Metals bioaccumulate when passed from a lower trophic level to the next higher trophic level and seriously deteriorate metabolic functions of organisms. Natural reduction in acidity and subsequent metal concentration in AMD is only possible if there are sufficient carbonates in the coal rocks (Miranda *et al.* 2010).

The second kind of WW is that which is generated from coal washeries during coal washing. The mined-out coal is sent to coal washeries through a conveyor belt, wherein its impurities are removed through specific gravity-based processes, to increase its heating value (Ghose 2001). The process generates a huge amount of coal slurry having large amounts of solids, chemical oxygen demand (COD) and metals. This effluent is often disposed of in surface waters which affects aquatic life by having a blanketing effect. Optionally it is also injected into abandoned underground mines (Yan *et al.* 2012). In the event, the process also results in loss of coal fines, usually 6–10 tonnes per day from a single washery plant (Tiwary & Dhar 1994; Ghose 2001).

The third and fourth kind of WW is generated from steel plants and TPPs respectively, which are responsible for steel production and electricity generation from the washed coal. The former makes metallurgical coke from coal through carbonization for further use in blast furnaces, which ultimately generates coke oven WW having highly hazardous nitrogenous, phenolic and other organic pollutants. The contaminants have the property to migrate to long distances from disposal sites and are genotoxic as well as carcinogenic to the living organisms (WHO 1997; Pal *et al.* 2011; Sharma & Philip 2016). Presence of these pollutants in surface water largely increases the oxygen demand and rapidly destroys the aquatic life. Eutrophication of the water bodies are observed due to rapid phenol degradation (Yu *et al.* 2016). TPPs generate fly ash (FA) through coal combustion. FA contains many heavy metals attached to its alumino-silicate matrix, which are often 4–10 times higher than the parent coal and are readily leachable in aqueous medium (Maiti & Prasad 2016). These metals find their way through wet and dry disposal sites of FA. Wet or slurry form disposal is done in ponds, from which the leachate left after FA settling often overflows to surface water bodies during the monsoon or leaches into groundwater through unlined ash ponds; also the ash itself can spill out through breached earthen walls (Yao *et al.* 2015). Dry disposal of FA creates huge unstable dumps which are the primary cause of slurry erosion during the monsoon. The dumps also lead to blowing of fine particles of FA which can also deposit on water bodies causing turbidity and metal pollution (Stefaniak *et al.* 2015).

In view of the above problems various laws have been formulated, which instruct the related industries to treat the WW up to a standard quality before discharge (EPR 1986; WHO 1997; BIS 2012). In this regard an extensive literature survey has been done to advocate possible treatment strategies for the WWs based on their individual characteristics, recent developments, and eco-friendly nature, while also addressing their benefits and challenges.

MINE WATER AND TREATMENT

Opencast mining encounters a permanent flow of water into mine pits along with subsequent loss of water from the nearby aquifers; as a result the communities living near the mine sites suffer from water scarcity. Annually only 13% of MW is reutilized for sprinkling and dust suppression in sites and a majority amount of the water is disposed of (obtained from an unpublished report of Mines of India). The amount of water depends on the size of mine. For example, different coal mine subsidiaries in India release 0.07–0.41 Mm^3 of MW every day and the total amount of water released per day is 1.24 Mm^3 (Debnath 2013). The mine water is characterized by dissolved solids, hardness, alkalinity, calcium, magnesium, iron and manganese (Table 1), at concentrations which are comparatively higher than the standard drinking water limits (BIS 2012). However, these contaminants can be easily removed by simple cost-effective techniques to achieve the purity level of drinking water (Figure 1).

Table 1 │ Characteristics of mine water, acid mine water, coal washery effluents, coke plant wastewater, and fly ash leachates

Parameters	Mine water[a]	Acid mine water	Coal washery effluent[b]	Coke plant wastewater[c]	Fly ash leachate[d]	Discharge limits[e]
pH	5.02–8.7	2.9–5.8	2.5–8.2	6.5–11.5	4.4–12.9	4–12
Colour, Hazen unit	<2.0	–	–	–	–	<5–15
Turbidity, NTU	–	–	5,387–23,360	84–528	–	1–5
Odour	Agreeable	–	–	–	–	Agreeable
Total suspended solids	–	–	110–30,000	2–712	12–140	15–50
Total dissolved solids	174–1,510	–	291–729	1,920	142–1,743	1,000–2,000
Alkalinity	132–488	–	1	224–17,200	41–681	200–600
Chloride	4–92	–	184	2,730	3–95	350–700
Sulphide	–	–	–	1.4–49	–	0.05–0.2
Sulphate	5–749	489–14,920	66–564	–	49–916	300–500
Nitrate	0.02–3	–	0.15–0.37	–	–	10–20
Ammonium nitrogen	–	–	–	49–520	0.04–0.64	5–10
Total Kjeldahl nitrogen	–	–	–	50–1,625	–	50
Biological oxygen demand	–	–	1,001	60–5,450	–	15
Chemical oxygen demand	–	–	192–6,468	81–16,000	–	100
Total organic carbon	–	–	–	100–4,390	–	50
Phosphorus	–	–	–	–	0.01–0.08	3–30
Fluoride	0.03–2.05	–				50
Hardness	390–712	–	358–720	–	105–985	200–600
Calcium	30–484	136–309	118–133	–	32–17,250	150–200
Magnesium	24–400	67–115	16	–	0.4–352	150–200
Sodium	–	–	30	–	17–601	200
Iron	0.061–0.371	50–4,537	0.13–212	–	0.02–6.7	1–20
Aluminium	–	7–800	–	–	1.4–373	5
Nickel	–	–	0.06	–	0.03–2.1	0.02–0.5
Manganese	0.018–12.93	15–155	0.07	–	0.01–36.4	1–5
Lead	0.018–0.021	–	–	–	0.01–2.8	0.1–2
Cadmium	–	–	0.01	–	0.001–0.8	0.003–0.2
Zinc	0.012–1.533	0.01–4	–	–	0.01–37	1–10
Copper	0.008–0.023	73	–	–	0.01–1.7	0.2–10
Arsenic	<0.01	–	–	–	0.28	0.1–1
Selenium	<0.01	–	–	–	0.002–2.4	0.05–0.5
Chromium	<0.01	–	–	–	0.004–3.3	0.05–0.5
Barium	–	–	–	–	0.1–1.32	0.7–4
Beryllium	–	–	–	–	0.01–0.2	0.3
Mercury	–	–	–	–	0.038	0.001–0.1
Boron	–	–	–	–	0.3–109	0.5–2
Molybdenum	–	–	–	–	0.06–3.92	0.05–1
Lithium	–	–	–	–	0.68–26.3	10
Vanadium	–	–	–	–	0.3–1	1
Phenols	0.002	–	–	50–1,650	–	0.1–1.2
Oil and grease	–	–	1.7–4.6	4.7–1,250	–	5–15
Cyanide	–	–	–	0.1–210	0.01	0.05–2

All parameters are in mg L^{-1} except pH, colour, turbidity.

[a]TERI (2013) and ECL (2014) (non-lignite mines).

[b]Ghose (2001), Das *et al.* (2006), Tiwary & Dhar (1994), Menkiti & Onukwuli (2011a, 2011b), Menkiti *et al.* (2011) and Nnaji *et al.* (2014).

[c]Zhang *et al.* (2009), Zhao *et al.* (2009), Zhang *et al.* (2010), Wei *et al.* (2012), Pal & Kumar (2014), Ozyonar & Karagozoglu (2015), Yu *et al.* (2015), Sharma & Philip (2016), Yu *et al.* (2016) and Zhao *et al.* (2017).

[d]Chu *et al.* (1978), Eisenberg *et al.* (1986), Nathan *et al.* (1999), Baba & Kaya (2004), Sarode *et al.* (2010), and Silva *et al.* (2010).

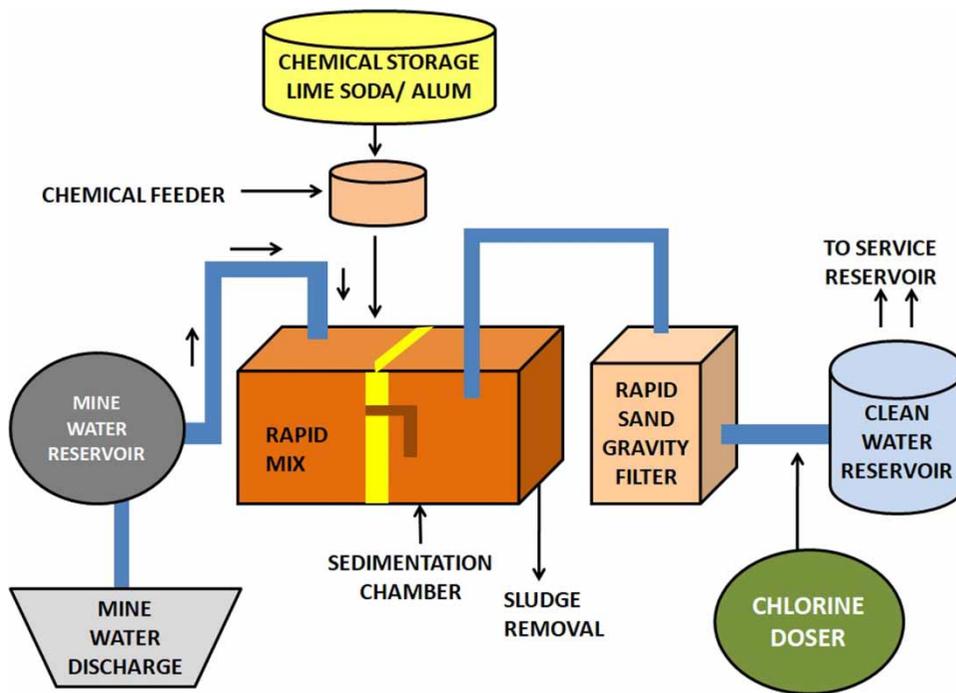[e]BIS (2012), Ministry of Environment and Water Resources (1986) and RGC (2009).

Figure 1 | Low-cost treatment for mine water.

The technique includes removal of floating impurities, followed by storage, and sedimentation of coarser materials in horizontal flow tanks. The dimensions of the tanks would depend on the capacity of the water treatment plant. The settled particles can be removed periodically after formation of a sludge zone of >0.8 m, followed by aeration to remove odours and precipitation of iron as well as manganese. Hardness can be removed by rapid dissolution of lime-soda. Coagulants such as alum conjugated with $FeSO_4$ or lime can be added to remove turbidity. Final disinfection can be ensured through chlorination or ozone treatment. A few highly sophisticated techniques such as nanofiltration (NF), reverse osmosis (RO) and ion exchange are practised in some mines across the globe, which remove salt ions, total dissolved solids, hardness, alkalinity, ammonia and metals (USEPA 2014). However, they extend the budget of the mining industry and are unfeasible for the developing countries.

On the other hand, pollutants present in AMD (Table 1) are remediated through biological procedures (Table 2) such as passive remediation using sulphate reducing bacteria (SRB) in bioreactors and wetlands. Metabolically the bacteria utilize the carbon and nitrogen source of a substrate and produce hydrogen sulphide in anaerobic conditions, which in turn reduces dissolved metals to sulphides. The later precipitates are ultimately absorbed in sedimentary

deposits. Industrial utilization of this process can treat AMD and induce alkalinity in it. Although the process requires minimal energy, it is less effective at high flow volumes and metal concentrations (Wieder 1989; Greben *et al.* 2009). This technique can be supported through installing anoxic limestone drains (ALDs), which increase the metal removal efficiency by 30%, add bicarbonate alkalinity and also have a lifetime of >20 years (Hedin *et al.* 1994; Ziemkiewicz *et al.* 2003). These ALDs are also affected in presence of highly acidic AMD with a coating of reddish iron oxyhydroxide within 48 h of contact. This can be reduced by using CO_2 (Hammarstrom *et al.* 2003). Coupling of ALD with SRB (or zinc-tolerant SRB) is known as successive alkalinity-producing systems, which can also be installed as vertical passage systems to reduce area requirement (Kepler & McCleary 1994). This integrated technique has been effective in reducing high sulphate and zinc in AMD (Castillo *et al.* 2012). Macrocapsules having a pH-sensitive polymer and a phosphate buffer are better than limestone for AMD treatment (Aelion *et al.* 2009).

Substrates which have been studied in artificially constructed anaerobic reactors for efficient AMD treatment are spent mushroom compost (Dvorak *et al.* 1992; Christensen *et al.* 1996), degradation products of grasses to remove sulphate (Greben *et al.* 2009), mixture of cow manure, mushroom compost, sawdust, gravel, limestone and sediment

Table 2 | Treatment procedures for acid mine drainage

Material used	Scale	Results	Reference
Wetlands or with sulphate reducing bacteria	*In situ*	8–81% acidity, Fe, Al, Mn, SO_4 reduced; pH and alkalinity increased from 3 to 7 and from 0 to 1,077 mg L^{-1} respectively	Wieder (1989) and McIntire & Edenborn (1990)
Anaerobic reactor + mushroom compost + sulphate reducing bacteria	Pilot	95% of Al, Cd, Fe, Mn, Ni, Zn precipitated as sulfides, hydroxides, carbonates	Dvorak *et al.* (1992)
Anoxic limestone drains	*In situ*	17–30% of SO_4, Fe, Mn, K, Na, Ca, Mg decreased	Hedin *et al.* (1994)
Sand bed + crushed stones + sulphate reducing bacteria	Bench	pH increased and metals decreased after 203 days	Christensen *et al.* (1996)
Permeable reactive wall (organic matter + sulphate reducing bacteria)	*In situ*	Fe decreased from 1,300 to 40 mg L^{-1}, pH and alkalinity increased from 5.8 to 7.0 and from 0 to 600 mg L^{-1} respectively	Benner *et al.* (1997)
Methanol + sulfate reducing bioreactor	Bench	88% SO_4 reduced, Fe decreased from 100 to 2 mg L^{-1}, pH increased	Tsukamoto & Miller (1999)
Chitin	Bench	pH increased from 3 to 7, alkalinity increased from 0 to 235 mg L^{-1}, acidity decreased from 192 to 114 mg L^{-1}, SO_4 decreased from 489 to 303 mg L^{-1}, >80% Fe, Al, Mn reduced after 9 days	Daubert & Brennan (2007)
Eichhornia crassipes, Lemna minor	Bench	Reduced metals in 21 days	Mishra *et al.* (2008)
Cellulose degradation products	Bench	SO_4 reduced by >78%, iron precipitated as FeS	Greben *et al.* (2009)
Macrocapsules + pH-sensitive polymer + phosphate buffer	Bench + field	pH increased from 3 to 6; metals and phosphate decreased	Aelion *et al.* (2009)
Zn-tolerant sulphate reducing bacteria	Bench	Completely removed Zn as sulphide sphalerite, wurtzite	Castillo *et al.* (2012)
Nanofiltration – 2540 membrane	Bench	Removed As, Sb, Pb, Hg at moderate pressure	Sierra *et al.* (2013)
NaP1 zeolite from coal fly ash	Bench	Zeolite removed As, Ni, Cu, Ca, Fe, Mn at 10 g L^{-1}	Cardoso *et al.* (2015)
Mussel shell + sulfate reducing bioreactor	Bench	Removed 86–90% Al, Fe, Cu, Zn; pH and alkalinity increased to 6 and 350 mg L^{-1} respectively	Uster *et al.* (2015)
Passive batch bioreactor-manure + compost + sawdust + gravel + limestone + sediment	Bench	pH and alkalinity increased, SO_4 reduced by >70%, Fe and Zn removed by >99% after 45 days	Vasquez *et al.* (2016)
Bio-electrochemical system	Bench	SO_4 reduced to <550 mg L^{-1}; Al, Fe, Zn was precipitated	Pozo *et al.* (2017)
Microspora tumidula	Bench	Accumulation of sulphur and phosphorus in algae at pH 5	Oberholster *et al.* (2017)

(Vasquez *et al.* 2016), mussel shells (Uster *et al.* 2015) and coagulants obtained from chitinous material (Daubert & Brennan 2007). More than 95% of the activity of the substrates can be regained by adding reducing equivalents such as methanol to the substrate (Tsukamoto & Miller 1999). Macroalgae can treat AMD in hybrid systems, which in turn also increases the macroalgae chlorophyll content (Oberholster *et al.* 2017). Metals in AMD can be removed by aquatic plants (*Eichhornia crassipes, Lemna minor*) which accumulate 10 times more metals in the roots, without showing any toxicity symptoms (Mishra *et al.* 2008), zeolites synthesized from coal FA (Cardoso *et al.* 2015), and bio-electrochemical systems (Pozo *et al.* 2017) without any extra chemical dosing and with reduced sludge formation. Earlier field applications in this aspect includes installation of an artificial permeable reactive wall perpendicular to the groundwater flow, which helped in treating AMD in a time period less than a year while staying effective for at least 15 years (Benner *et al.* 1997). Overall, AMD can be treated by combined strategies (Figure 2) such as wetlands with SRB, macroalgae, aquatic plants, different organic substrates, and ALDs, and can be
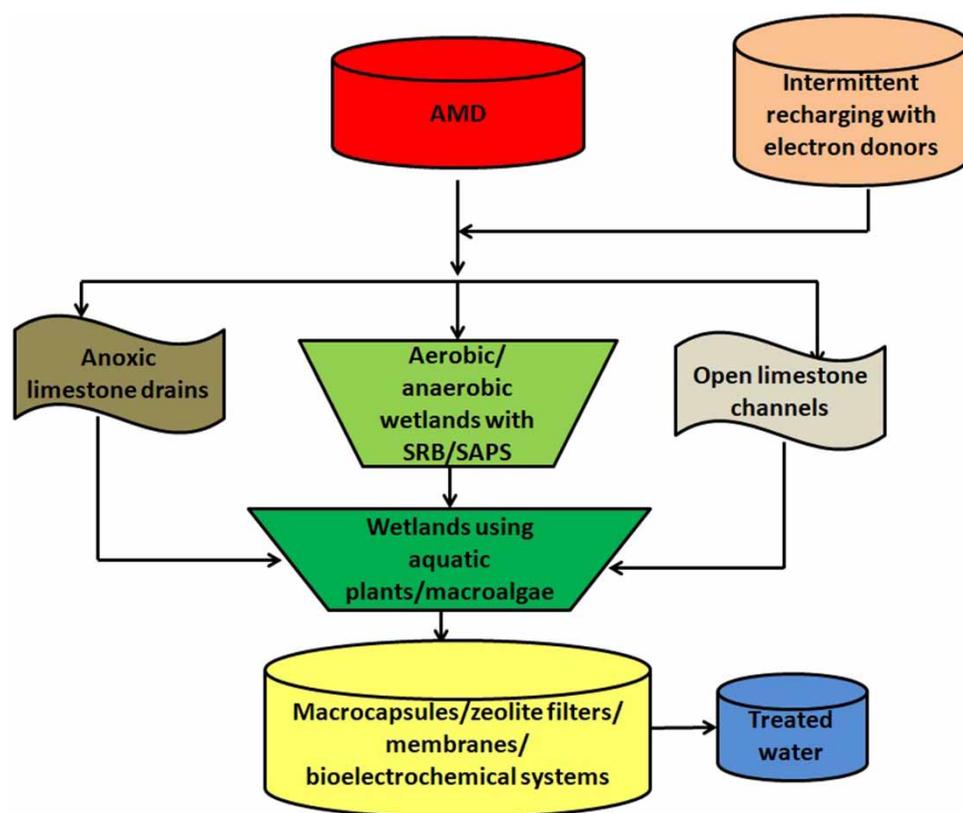
Figure 2 │ Treatment procedures for acid mine drainage (AMD: acid mine drainage; SRB: sulphate reducing bacteria; SAPS: successive alkalinity producing systems).

further treated with macrocapsules, natural coagulants, membranes or zeolites.

COAL WASHERY EFFLUENTS AND TREATMENT

The huge amount of WW released by coal washeries (approximately 300–500 m³ of effluent each day per plant) can be treated for reuse in coal washing and to reduce fresh water consumption, because, as per estimates, every 100 tonnes of coal requires 6×10^5 to 2×10^6 gallons (2,270–7,570 m³) of water for washing (Ghose 2001). Various parameters in the effluents (Table 1) have values above standard limits (EPR 1986; WHO 1997; BIS 2012). The pollutants that are mainly coarser solids can be removed through sedimentation, and dissolved solids by coagulants (Table 4), wherein oppositely charged ions destabilize stable colloids and result in settleable flocs (Menkiti & Onukwuli 2011a, 2011b).

Poly-electrolytes such as alum, dioctyl-sodium-sulpho-succinate, N-cetyl-N,N,N-trimethyl ammonium bromide and synthetic flocculants such as Morarfloc-A or True-floc are mostly used (Folkard & Sutherland 1996). Although synthetic flocculants are more effective than alum as they remove more solids in less time and require a much smaller dose (1 mg L^{-1}) than the latter $(30–50 \text{ mg L}^{-1})$, they are linked with many health effects (Ghose 2001). Therefore natural products or coagulants should be considered, which not only remove pollutants, but produce less sludge, ensure potability, and are biodegradable and cost-effective. Literature has reported use of bark resins, ashes, and seaweed extracts by villagers for water treatment (Folkard & Sutherland 1996). Coagulants can be prepared from seeds of *Moringa oleifera*, *M. stenopetala*, *Hibiscus sabdariffa* and *Strychnos potatorum* (Kapse *et al.* 2017), or from the byproducts obtained during oil extraction from the seeds (Ghebremichel 2004). Due to presence of amino acids such as arginine, *Moringa* seed preparations can outperform Al_2SO_4 to remove 95% of the pollutants in coal washery effluent (Menkiti *et al.* 2011). Pilot scale studies have also proved the efficiency of coagulants from *Mucuna sloanei* and *Afzelia bella* seeds for treatment of WW (Menkiti *et al.* 2010; Menkiti & Onukwuli 2011a, 2011b). Coagulants from natural starch and chitin also show similar results (Table 3) and can be prepared by electrolyzing a solution of cassava starch (obtained from milled cassava tubers) and calcium hypochlorite in 1:2 ratio followed by mixing

Table 3 | Treatment of coal washery effluents using coagulants

Coagulant	Pollutants	Dosage	Removal efficiency	Reference
Starch + alum + FeCl$_3$	Turbidity, suspended solids	30–250 mg L^{-1}	pH = 4, efficiency => 90%	Nnaji *et al.* (2014)
Fly ash	Chemical oxygen demand, suspended solids	10 g L^{-1}	pH = 9, efficiency is > 90%	Yan *et al.* (2012)
Chitin	Turbidity, suspended solids	10 mg L^{-1}	pH = 8, efficiency is > 90%	Menkiti & Onukwuli (2011a, 2011b)
Afzelia bella seed		0.2–0.3 kg m^{-3}	pH = 2–6	
Mucuna seed		0.25 kg m^{-3}		Menkiti *et al.* (2010)
Periwinkle shell		0.4 kg m^{-3}		Menkiti *et al.* (2009)

Table 4 | Treatment procedures for coke oven wastewater

Material used	Removal efficiency	Reference
Electrochemical oxidation with PbO$_2$-Ti anode	>90% of COD and ammonia removed	Chiang *et al.* (1995)
Submerged biofilm + activated sludge	80–99% efficient	Junxin *et al.* (1996)
A$_1$-A$_2$-O + *Burkholderia pickettii*	16–59% COD removed	Jianlong *et al.* (2002)
Adsorption catalytic oxidation	>90% efficient	Hong *et al.* (2003)
Ultrasonic irradiation + catalytic oxidation + activated sludge	Activated sludge + ultrasonic irradiation or ultrasonic irradiation + FeSO$_4$ removed 48–81% and 96% pollutants respectively	Ning *et al.* (2005)
Pilot plant sequential batch reactor	85–99% of ammonia, COD, thiocyanate, phenol removed	Maranon *et al.* (2008)
ZVI = 10 g L^{-1} active carbon + 30 g L^{-1} iron	44% removal of COD at pH 4	Lai *et al.* (2007)
Nitrifying–denitrifying biofilm	94% removal of COD + ammonia	Rong *et al.* (2007)
BDD anode system	Removal of TOC + NH$_3$-N	Zhu *et al.* (2009)
Manganese + magnesium ore	70–100% removal of phenols, COD, sulphide, ammonia, phosphate	Chen *et al.* (2009)
A$_1$-A$_2$-O-MBR	71–99% removal of COD, phenol, ammonia, TN	Zhao *et al.* (2009)
Biofilm reactor + ZVI	92% removal of COD, ammonia, TN, phenols, humic acids	Lai *et al.* (2009)
Phanerochaete chrysosporium on wood chips of Italian poplar	72–87% removal of phenol, COD in 6 days	Lu *et al.* (2009)
200 g L^{-1} activated coke	91% removal of COD, color at 40 °C	Zhang *et al.* (2010)
Vacuum distillation + NaOH	99% COD removed	Mao *et al.* (2010)
Fenton oxidation + iron + 0.3 M H$_2$O$_2$	44–50% COD and 95% phenol removed at pH <6.5	Chu *et al.* (2012)
A$_1$-A$_2$-O + MBR + nanofiltration + reverse osmosis	45–99% removal of COD, BOD, ammonia, phenol, TCN, thiocyanate, fluoride	Jin *et al.* (2013)
Super critical water oxidation + H$_2$O$_2$ + salt separator	99% removal efficiency at 650 °C	Du *et al.* (2013)
Membrane distillation + pre-coagulation	>90% removal of non-volatile organic pollutants; poly-aluminum chloride coagulated volatile organic pollutants	Li *et al.* (2016)

COD, chemical oxygen demand; TN, total nitrogen; TOC, total organic carbon; A1-A2-O, anaerobic–anoxic–aerobic biofilm system; ZVI, zero-valent iron; MBR, membrane bioreactor; BDD, boron-doped diamond; BOD, biochemical oxygen demand; TCN, total cyanide.

with FeCl$_3$ or mixing the extracted chitin coagulant with alum and FeCl$_3$ (Menkiti *et al.* 2008, 2009; Menkiti & Onukwuli 2011a, 2011b; Nnaji *et al.* 2014). FA-based coagulants were also studied by Yan *et al.* (2012). The macro-fungus *Pleurotus ostreatus* showed removal of manganese, zinc, nickel, copper, cobalt, chromium, iron, and lead from

50% diluted WW (Vaseem *et al.* 2017). Thus a hypothetical coal washery treatment plant can be proposed which should incorporate an adequate sedimentation time followed by a wise use of coagulants. The process can also ensure a possibility for recovery of coal fines.

COKE PLANT WASTEWATER AND TREATMENT

Every 1,000 tons of coke production requires 4,000 m^3 of freshwater and generates 1,000 m^3 of coke oven WW during cooling of hot coke over different coolers (Sharma & Philip 2016). This WW contains high amounts of ammonia, phenol, cyanide, thiocyanate, total nitrogen, suspended matter and COD (Table 1) at a concentration higher than the standard permissible limits (EPR 1986). Pollutants removal from the WW is either done by concentration or destructive processes (Figure 3). In the concentration process the pollutants are recovered by dissolving them out by organic solvents which have a high distribution coefficient for the particular pollutant; some of the solvents are methyl isobutyl ketone, di-isopropyl ether and butyl acetate which extracts phenol (Lu *et al.* 2009). Similarly, cyanide is often precipitated as valuable iron complexes using ferric solutions which also remove suspended matter, oil and grease. Ammonia is removed and recovered through steam stripping, wherein alkaline ammoniacal liquor is reacted with steam. Synthetic zeolites can also remove ammonia through ion-exchange technique and advantageously can be regenerated with low-cost brine (Chu *et al.* 2012; Cardoso *et al.* 2015). The destructive treatment procedures are listed in Table 4, and mainly degrade the pollutants by various agents. For example advanced Fenton oxidation process with H_2O_2 can remove COD and phenol; activated coke can remove maximum COD and color at 40 °C (Zhang *et al.* 2010); zerovalent iron (ZVI) having carbon and iron can also remove COD through coagulation, precipitation and oxidation–reduction processes compared to ferric sulphate or activated carbon alone (Hong *et al.* 2003; Lai *et al.* 2007); electrochemical oxidation in presence of lead dioxide coated titanium anode can remove COD and ammonia (Chiang *et al.* 1995).

However, boron-doped diamond anode systems are more efficient than lead dioxide anodes as the energy consumption is only 60% (Zhu *et al.* 2009). Manganese and magnesium ores can oxidize COD, ammonia, phenols, and sulphides under acidic conditions (Chen *et al.* 2009); supercritical oxidation of water with H_2O_2 and 300% excess oxygen in a continuous-flow reactor can remove 99% of pollutants (Du *et al.* 2013); vacuum distillation with caustic soda can remove 99% of COD (Mao *et al.* 2010). Bio-augmentation is another method which is used in removing
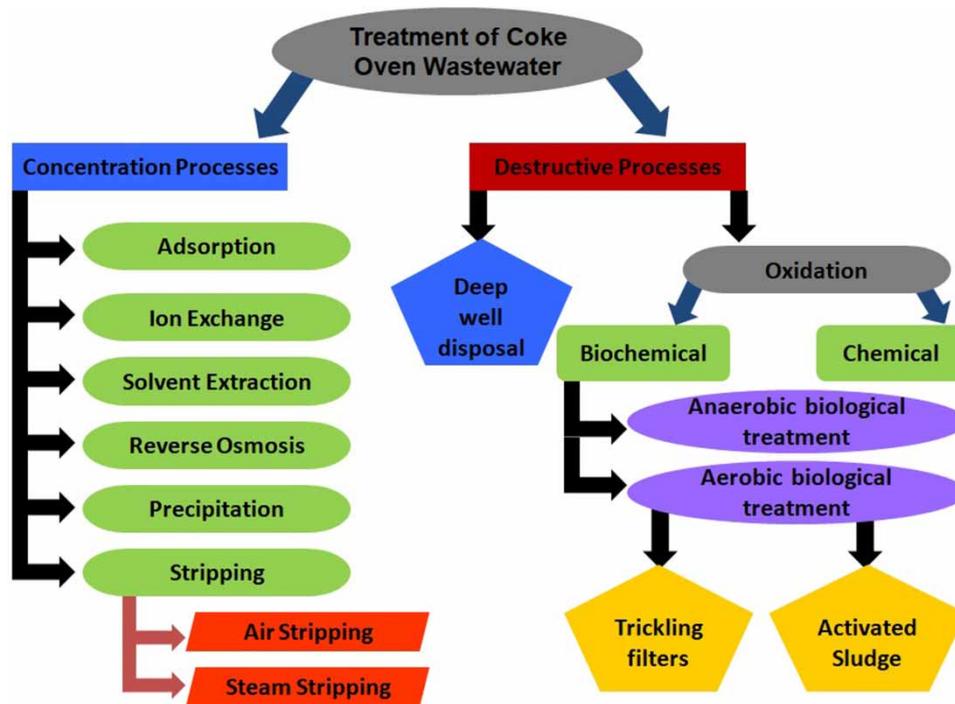

Figure 3 | Treatment processes of coke oven wastewater.

recalcitrant organic compounds from WW. Aerobic bacteria usually degrade pollutants at optimum pH, temperature, oxygen, nutrients, biomass concentrations and residence time (Chu *et al.* 2012). Jianlong *et al.* (2002) used a quinoline degrading bacterium, *Burkholderia pickettii*, for bioaugmenting the oxic reactor of an anaerobic–anoxic–aerobic (A1-A2-O) system. *Nitrosomonas* bacteria can oxidize ammonia to nitrite while *Nitrobacter* oxidizes nitrite to nitrate (Jianlong *et al.* 2002). They can be attached to fixed media to form fixed-film bioreactors or hybrid biofilms to remove pollutants from WW passing through them (Rong *et al.* 2007). WW passed through the immobilized fungus *Phanerochaete chrysosporium* reduced phenol and COD (Lu *et al.* 2009). Biofilm reactors with ZVI have also been used in practical applications (Lai *et al.* 2009). Ammonia can also be oxidized by activated sludge treatment process as well as oxidation ditches, which have a longer residence time than the former (Schroeder 1977; Ning *et al.* 2005), whereas lagoon systems have 5–7 days residence times and higher temperature (Kargi & Uygur 2002). Activated sludge plants generally involve three reactors which remove COD, followed by phenols, ammonia and thiocyanate, and finally nitrate. Methanol can be added as an external carbon source in such systems (Vazquez *et al.* 2006). Sequencing batch reactors (SBRs) also have three reactors which undertake simultaneous clarification along with treatment; the reactors are namely stripping tank, neutralization tank and SBR tank (Maranon *et al.* 2008). Membrane bioreactors (A1-A2-O-MBR) include an extra anoxic basin where the screened raw WW is collected, and then passed to pre-aeration as well as MBR basins to remove pollutants (Zhao *et al.* 2009). However, these reactors require frequent membrane cleaning processes to prevent membrane fouling. The propensity for membrane fouling can be reduced by coupling membrane distillation with pre-coagulation for biologically treated WWs, which can remove salts, and volatile and non-volatile organic pollutants through coagulation with poly-aluminum chloride (Li *et al.* 2016). Submerged biofilm-activated sludge hybrid system can remove maximum ammonia and COD from WW (Junxin *et al.* 1996). Additionally, ultrasonic irradiation can also be coupled with catalytic oxidation or activated sludge process, which shows more efficiency in treatment (Ning *et al.* 2005). Anammox reactors are a type of system which undertakes anaerobic ammonium oxidation using planctomycete bacteria (Aksogan *et al.* 2003). Down-flow hanging sponge reactors have a series of hanging polyurethane sponges with diverse microbial biomass upon which ammoniacal WW is trickled. The diverse microbial biomasses are for establishing ecosystems with

long food chains and reduction in sludge production during treatment (Zhang *et al.* 2008). Practically, A_1-A_2-O systems can be coupled with MBR, NF and RO systems for WW treatment (Jin *et al.* 2013). However, the disadvantage of such systems is further treatment and disposal of the concentrates from NF-RO units.

FLY ASH LEACHATES AND TREATMENT

FA leachates contain varying concentrations of metals, as shown in Table 1, which often surpass the limits of Indian drinking water standards (BIS 2012). Some management practices for these contaminated WWs include mainly prevention of their generation through covering dumps with topsoil and reducing contact of FA with rainwater. The buffering capacity of soil attenuates the metals in organic matter. Transportation of FA as high concentrated slurry during disposal can also minimize leachate generation and water consumption. Demineralization of coal before its burning is a topic of recent research, which can control release of many pollutants in all the WWs. Even if the leachates are formed, their migration to groundwater can be reduced by an adequate liner below the ash ponds, and a leachate collection system wherein the leachate is collected. Along with these the surface water flow should also be controlled (Maiti & Prasad 2016). Attenuating barriers composed of sand, iron, and bentonite can reduce chromium from 25 to 0.0025 mg L^{-1} in alkaline leachates (Astrup *et al.* 2000). Flue gas desulphurization gypsum can precipitate 40–100% of metals in acidic leachates as sulfides (Jayaranjan & Annachhatre 2012). However, metals in acidic leachates can be removed by similar procedures as mentioned for AMD, viz. use of coagulants, bio-electrochemical technology, etc. Extensive research is required for large scale treatment of leachates using latest developments in the field of water treatment.

CHALLENGES

Despite the usefulness of the above treatments, none of them if used alone can be outstanding in terms of amount of wastewater to be treated, contaminant removal potential and treatment cost. The specific challenges of the above techniques are as follows.

(1) In the case of biological treatments, despite being cost-effective and eco-friendly, they can take a large span of

time to treat the huge amount of WW produced in real conditions.

(2) Passive remediation techniques are expensive for long-term problems such as AMD and therefore can be combined with other technologies.

(3) Although advanced oxidation and membrane techniques are primary processes for advanced treatment of coke oven WW, they are expensive and undergo membrane fouling. Studies should be focused on reducing treatment cost along with techniques to control membrane fouling.

(4) Very few field studies have been found which could uphold the wide applicability and sustainability of the treatment procedures. Hence, future studies should be focused towards scaling up the pilot scale studies with the actual coal-related effluents.

CONCLUSION

A wise analysis of advantages and challenges suggest that the treatment methods can potentially purify water to the drinking level stage when used collaboratively. After further validation studies they can be practically implemented in areas where fresh water is scarce. Advantageously simple treatment techniques can remediate mildly polluted WW with less expense. There is a growing inclination towards WW treatment through safer eco-friendly techniques; hence biological approaches can be used in an integrated manner with conventional techniques to reduce use of chemicals and formation of sludges, and ensure potability, cost-effectiveness and regeneration of treatment materials.

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DECLARATION OF INTEREST

All authors confirm that they have no conflict of interest.

REFERENCES

Aelion, C. M., Davis, H. T., Flora, J. R., Kirtland, B. C. & Amidon, M. B. 2009 Application of encapsulation (pH-sensitive polymer and phosphate buffer macrocapsules): a novel approach to remediation of acidic ground water. *Environmental Pollution* **157** (1), 186–193.

Aksogan, S., Basturk, A., Yuksel, E. & Akgiray, O. 2003 On the use of crushed shells of apricot stones as the upper layer in dual media filters. *Water Science and Technology* **48** (11), 497–503.

Astrup, T., Stipp, S. L. S. & Christensen, T. H. 2000 Immobilization of chromate from coal fly ash leachate using an attenuating barrier containing zero-valent iron. *Environmental Science and Technology* **34** (19), 4163–4168.

Baba, A. & Kaya, A. 2004 Leaching characteristics of fly ash from thermal power plants of Soma and Tunçbilek, Turkey. *Environmental Monitoring and Assessment* **91** (1), 171–181.

Benner, S. G., Blowes, D. W. & Ptacek, C. J. 1997 A full-scale porous reactive wall for prevention of acid mine drainage. *Groundwater Monitoring and Remediation* **17** (4), 99–107.

BIS (Bureau of Indian Standards) 2012 Drinking water specifications IS 10500.

Cardoso, A. M., Paprocki, A., Ferret, L. S., Azevedo, C. M. & Pires, M. 2015 Synthesis of zeolite Na-P1 under mild conditions using Brazilian coal fly ash and its application in wastewater treatment. *Fuel* **139**, 59–67.

Castillo, J., Perez-Lopez, R., Caraballo, M. A., Nieto, J. M., Martins, M., Costa, M. C., Olias, M., Ceron, J. C. & Tucoulou, R. 2012 Biologically-induced precipitation of sphalerite–wurtzite nanoparticles by sulfate-reducing bacteria: implications for acid mine drainage treatment. *Science of the Total Environment* **423**, 176–184.

Chen, T., Huang, X., Pan, M., Jin, S., Peng, S. & Fallgren, P. H. 2009 Treatment of coking wastewater by using manganese and magnesium ores. *Journal of Hazardous Materials* **168** (2), 843–847.

Chiang, L. C., Chang, J. E. & Wen, T. C. 1995 Electrochemical oxidation process for the treatment of coke-plant wastewater. *Journal of Environmental Science and Health, Part A* **30** (4), 753–771.

Christensen, B., Laake, M. & Lien, T. 1996 Treatment of acid mine water by sulfate-reducing bacteria; results from a bench scale experiment. *Water Research* **30** (7), 1617–1624.

Chu, T. Y. J., Ruane, R. J. & Krenkel, P. A. 1978 Characterization and reuse of ash pond effluents in coal-fired power plants. *Water Pollution Control Federation* **50** (11), 2494–2508.

Chu, L., Wang, J., Dong, J., Liu, H. & Sun, X. 2012 Treatment of coking wastewater by an advanced Fenton oxidation process using iron powder and hydrogen peroxide. *Chemosphere* **86** (4), 409–414.

Das, B., Prakash, S., Biswal, S. K. & Reddy, P. S. R. 2006 Settling characteristics of coal washery tailings using synthetic polyelectrolytes with fine magnetite. *Journal of the Southern African Institute of Mining and Metallurgy* **106** (10), 707.

Daubert, L. N. & Brennan, R. A. 2007 Passive remediation of acid mine drainage using crab shell chitin. *Environmental Engineering Science* **24** (10), 1475–1480.

Debnath, A. K. 2013 *Sustainable Mining in India*. In: Energy Conclave. www.bengalchamber.com/energyconclave/year2013/ak-debnath.pdf.

Du, X., Zhang, R., Gan, Z. & Bi, J. 2013 Treatment of high strength coking wastewater by supercritical water oxidation. *Fuel* **104**, 77–82.

Dvorak, D. H., Hedin, R. S., Edenborn, H. M. & McIntire, P. E. 1992 Treatment of metal-contaminated water using bacterial sulfate reduction: results from pilot-scale reactors. *Biotechnology and Bioengineering* **40** (5), 609–616.

ECL 2014 *Final Environmental Impact Assessment & Environmental Management Plan.* (As per EIA Notification, 2006) for Cluster No. 10 (Group of Mines) Raniganj Coalfield Eastern Coalfields Limited, Regional Institute – I, Central Mine Planning & Design Institute Ltd.

Eisenberg, S. H., Tittlebaum, M. E., Eaton, H. C. & Soroczak, M. M. 1986 Chemical characteristics of selected flyash leachates. *Journal of Environmental Science and Health, Part A* **21** (4), 383–402.

EPR (Environmental Protection Rules) 1986 General standard for discharges of environmental pollutants Part A. In: *Effluents Notified at sl. no. 8.* (S. P. Gautam, ed.), Ministry of Environment and Forest, Department of Environment, Forest and Wild Life, Government of India, New Delhi, Schedule VI (rule 3A), pp. 545–547.

Equeenuddin, S. M., Tripathy, S., Sahoo, P. K. & Panigrahi, M. K. 2010 Hydrogeochemical characteristics of acid mine drainage and water pollution at Makum Coalfield, India. *Journal of Geochemical Exploration* **105** (3), 75–82.

Folkard, G. & Sutherland, J. 1996 *Moringa oleifera*: a tree and a litany of potential. *Agroforestry Today* **8** (3), 5–8.

Ghebremichel, K. A. 2004 Moringa *Seed and Pumice as Alternative Natural Materials for Drinking Water Treatment.* TRITA-LWR PHD, 1013.

Ghose, M. K. 2001 Design of cost-effective coal washery effluent treatment plant for clean environment. *Journal of Scientific and Industrial Research* **60**, 40–47.

Greben, H. A., Baloyi, J., Sigama, J. & Venter, S. N. 2009 Bioremediation of sulphate rich mine effluents using grass cuttings and rumen fluid microorganisms. *Journal of Geochemical Exploration* **100** (2–3), 163–168.

Hammarstrom, J. M., Sibrell, P. L. & Belkin, H. E. 2003 Characterization of limestone reacted with acid-mine drainage in a pulsed limestone bed treatment system at the Friendship Hill National Historical Site, Pennsylvania, USA. *Applied Geochemistry* **18** (11), 1705–1721.

Hedin, R. S., Watzlaf, G. R. & Nairn, R. W. 1994 Passive treatment of acid mine drainage with limestone. *Journal of Environmental Quality* **23** (6), 1338–1345.

Hong, L., Linxia, Z. & Keming, W. 2003 Study on the treatment of coke plant wastewater by adsorption catalytic oxidation process. *Industrial Water Treatment-Tianjin* **23** (5), 35–37.

Jayaranjan, M. L. D. & Annachhatre, A. P. 2012 Precipitation of heavy metals from coal ash leachate using biogenic hydrogen sulfide generated from FGD gypsum. *Water Science and Technology* **67** (2), 311–318.

Jianlong, W., Xiangchun, Q., Libo, W., Yi, Q. & Hegemann, W. 2002 Bioaugmentation as a tool to enhance the removal of refractory compound in coke plant wastewater. *Process Biochemistry* **38** (5), 777–781.

Jin, X., Li, E., Lu, S., Qiu, Z. & Sui, Q. 2013 Coking wastewater treatment for industrial reuse purpose: combining biological processes with ultrafiltration, nanofiltration and reverse osmosis. *Journal of Environmental Sciences* **25** (8), 1565–1574.

Junxin, L., Baozhen, W., Weiguang, L., Chengji, J., Xiangdong, C. & Lin, W. 1996 Removal of nitrogen from coal gasification and coke plant wastewaters in A/O submerged biofilm-activated sludge (SBF-AS) hybrid system. *Water Science and Technology* **34** (10), 17–24.

Kapse, G., Patoliya, P. & Samadder, S. R. 2017 Characterisation of coal washery effluent and optimisation of coagulation behaviour of *Moringa oleifera* seed as a coagulant. *Environmental Monitoring and Assessment* **189** (3), 133.

Kargi, F. & Uygur, A. 2002 Nutrient removal performance of a sequencing batch reactor as a function of the sludge age. *Enzyme and Microbial Technology* **31**, 842–847.

Kepler, D. A. & McCleary, E. C. 1994 Successive alkalinity-producing systems (SAPS) for the treatment of acidic mine drainage. *Bureau of Mines Special Publication SP 06B-94* **1**, 185–194.

Lai, P., Zhao, H. Z., Wang, C. & Ni, J. R. 2007 Advanced treatment of coking wastewater by coagulation and zero-valent iron processes. *Journal of Hazardous Materials* **147** (1–2), 232–239.

Lai, P., Zhao, H. Z., Zeng, M. & Ni, J. R. 2009 Study on treatment of coking wastewater by biofilm reactors combined with zero-valent iron process. *Journal of Hazardous Materials* **162** (2), 1423–1429.

Li, J., Wu, J., Sun, H., Cheng, F. & Liu, Y. 2016 Advanced treatment of biologically treated coking wastewater by membrane distillation coupled with pre-coagulation. *Desalination* **380**, 43–51.

Lu, Y., Yan, L., Wang, Y., Zhou, S., Fu, J. & Zhang, J. 2009 Biodegradation of phenolic compounds from coking wastewater by immobilized white rot fungus *Phanerochaete chrysosporium*. *Journal of Hazardous Materials* **165** (1), 1091–1097.

Maiti, D. & Prasad, B. 2016 Revegetation of fly ash – a review with emphasis on grass-legume plantation and bioaccumulation of metals. *Applied Ecology and Environmental Research* **14** (2), 185–212.

Mao, W., Ma, H. & Wang, B. 2010 Performance of batch vacuum distillation process with promoters on coke-plant wastewater treatment. *Chemical Engineering Journal* **160** (1), 232–238.

Maranon, E., Vazquez, I., Rodriguez, J., Castrillon, L., Fernandez, Y. & Lopez, H. 2008 Treatment of coke wastewater in a sequential batch reactor (SBR) at pilot plant scale. *Bioresource Technology* **99** (10), 4192–4198.

McIntire, P. E. & Edenborn, H. M. 1990 The use of bacterial sulfate reduction in the treatment of drainage from coal mines. In: *Proceedings of the 1990 Mining and Reclamation Conference and Exhibition.* West Virginia University, Morgantown, 2, 409–415

Menkiti, M. C. & Onukwuli, O. D. 2011a Coag-flocculation studies of *Afzelia bella* coagulant (ABC) in coal effluent using single and simulated multi angle nephelometry. *Journal of Minerals & Materials Characterization & Engineering* **10** (3), 279.

Menkiti, M. C. & Onukwuli, O. D. 2011b Impact of pH variation on coag-flocculation behaviour of chitin derived coag-flocculant in coal washery effluent medium. *Journal of Minerals & Materials Characterization & Engineering* 10 (15), 1391.

Menkiti, M. C., Igbokwe, P. K., Ugodulunwa, F. X. O. & Onukwuli, O. D. 2008 Rapid coagulation/flocculation kinetics of coal effluent with high organic content using blended and unblended chitin derived coagulant (CSC). *Research Journal of Applied Sciences* 3 (4), 317–323.

Menkiti, M. C., Nnaji, P. C. & Onukwuli, O. D. 2009 Coag-flocculation kinetics and functional parameters response of periwinkle shell coagulant (PSC) to pH variation in organic rich coal effluent medium. *Nature and Science* 7 (6), 1–18.

Menkiti, M. C., Nnaji, P. C., Nwoye, C. I. & Onukwuli, O. D. 2010 Coag-flocculation kinetics and functional parameters response of mucuna seed coagulant to pH variation in organic rich coal effluent medium. *Journal of Minerals & Materials Characterization & Engineering* 9 (2), 89.

Menkiti, M. C., Nwoye, C. I., Onyechi, C. A. & Onukwuli, O. D. 2011 Factorial optimization and kinetics of coal washery effluent coag-flocculation by *Moringa oleifera* seed biomass. *Advances in Chemical Engineering and Science* 1 (3), 125.

Ministry of Environment and Water Resources 1986 Ministerial Decision 5/86. Regulations for waste water re-use and discharge. *Law on the Conservation of the Environment and Prevention of Pollution*. Sultanate of Oman, Muscat.

Miranda, M. A., Sauer, A. & Shinde, D. 2010 *Mine the Gap: Connecting Water Risks and Disclosure in the Mining Sector.* World Resource Institute, Washington, DC, USA.

Mishra, V. K., Upadhyaya, A. R., Pandey, S. K. & Tripathi, B. D. 2008 Heavy metal pollution induced due to coal mining effluent on surrounding aquatic ecosystem and its management through naturally occurring aquatic macrophytes. *Bioresource Technology* 99 (5), 930–936.

Nathan, Y., Dvorachek, M., Pelly, I. & Mimran, U. 1999 Characterization of coal fly ash from Israel. *Fuel* 78 (2), 205–213.

Ning, P., Bart, H. J., Jiang, Y., De Haan, A. & Tien, C. 2005 Treatment of organic pollutants in coke plant wastewater by the method of ultrasonic irradiation, catalytic oxidation and activated sludge. *Separation and Purification Technology* 41 (2), 133–139.

Nnaji, P. C., Okolo, B. I. & Menkiti, M. C. 2014 Nephelometric performance evaluation of oxidized starch in the treatment of coal washery effluent. *Natural Resources* 5 (3), 79.

Oberholster, P. J., Cheng, P. H., Botha, A. M., Hobbs, P. & Hill, L. 2017 Assessment of selected macroalgae for use in a biological hybrid system for treating sulphur in acid mine drainage (AMD). *Journal of Applied Phycology* 30 (2), 1–10.

Ozyonar, F. & Karagozoglu, B. 2015 Treatment of pretreated coke wastewater by electrocoagulation and electrochemical peroxidation processes. *Separation and Purification Technology* 150, 268–277.

Pal, P. & Kumar, R. 2014 Treatment of coke wastewater: a critical review for developing sustainable management strategies. *Separation & Purification Reviews* 43 (2), 89–123.

Pal, S., Adhikari, K., Ghosh, S. & Mukherjee, S. N. 2011 Characterization of subsurface water near an industrial wastewater disposal site. *International Journal of Earth Sciences and Engineering* 4 (6), 437–441.

Pozo, G., Pongy, S., Keller, J., Ledezma, P. & Freguia, S. 2017 A novel bioelectrochemical system for chemical-free permanent treatment of acid mine drainage. *Water Research* 126, 411–420.

Rong, Q., Kun, Y. & Yu, Z. X. 2007 Treatment of coke plant wastewater by SND fixed biofilm hybrid system. *Journal of Environmental Sciences* 19 (2), 153–159.

RGC (Royal Government of Cambodia) 2009 *Effluent Standard for Pollution Sources Discharging Wastewater to Public Water Areas or Sewer. Sub Decree on Water Pollution Control*, 27, ANRK.BK., Kingdom of Cambodia, pp. 10–13.

Sarode, D. B., Jadhav, R. N., Khatik, V. A., Ingle, S. T. & Attarde, S. B. 2010 Extraction and leaching of heavy metals from thermal power plant fly ash and its admixtures. *Polish Journal of Environmental Studies* 6, 1325–1330.

Schroeder, E. D. 1977 *Water and Wastewater Treatment.* McGraw-Hill, New York, USA, pp. 288–305.

Sharma, N. K. & Philip, L. 2016 Combined biological and photocatalytic treatment of real coke oven wastewater. *Chemical Engineering Journal* 295, 20–28.

Sierra, C., Saiz, J. R. A. & Gallego, J. L. R. 2013 Nanofiltration of acid mine drainage in an abandoned mercury mining area. *Water Air and Soil Pollution* 224 (10), 1734.

Silva, L. F., Ward, C. R., Hower, J. C., Izquierdo, M., Waanders, F., Oliveira, M. L. S., Li, Z., Hatch, R. S. & Querol, X. 2010 Mineralogy and leaching characteristics of coal ash from a major Brazilian power plant. *Coal Combustion and Gasification Products* 2, 51–65.

Soni, A. K. & Wolkersdorfer, C. 2016 Mine water: policy perspective for improving water management in the mining environment with respect to developing economies. *International Journal of Mining Reclamation and Environment* 30 (2), 115–127.

Stefaniak, S., Miszczak, E., Szczepanska-Plewa, J. & Twardowska, I. 2015 Effect of weathering transformations of coal combustion residuals on trace element mobility in view of the environmental safety and sustainability of their disposal and use. I. Hydrogeochemical processes controlling pH and phase stability. *Journal of Environment Management* 156, 128–142.

TERI 2013 *Equitable Sharing of Benefits Arising from Coal Mining and Power Generation among Resource Rich States.* The Energy and Resources Institute, New Delhi, India.

Tiwary, R. K. & Dhar, B. B. 1994 Environmental pollution from coal mining activities in Damodar river basin, India. *Mine Water and the Environment* 13, 1–10.

Tsukamoto, T. K. & Miller, G. C. 1999 Methanol as a carbon source for microbiological treatment of acid mine drainage. *Water Research* 33 (6), 1365–1370.

USEPA 2014 *Reference Guide to Treatment Technologies for Mining-Influenced Water.* USEPA 542-R-14-001. Office of Superfund Remediation and Technology Innovation.

Uster, B., O-Sullivan, A. D., Ko, S. Y., Evans, A., Pope, J., Trumm, D. & Caruso, B. 2015 The use of mussel shells in upward-flow sulfate-reducing bioreactors treating acid mine drainage. *Mine Water and the Environment* 34 (4), 442–454.

Vaseem, H., Singh, V. K. & Singh, M. P. 2017 Heavy metal pollution due to coal washery effluent and its decontamination using a macrofungus, *Pleurotus ostreatus*. *Ecotoxicology and Environmental Safety* **145**, 42–49.

Vasquez, Y., Escobar, M. C., Neculita, C. M., Arbeli, Z. & Roldan, F. 2016 Selection of reactive mixture for biochemical passive treatment of acid mine drainage. *Environment Earth Science* **75** (7), 576.

Vazquez, I., Rodriguez, J., Maranon, E., Castrillon, L. & Fernandez, Y. 2006 Study of the aerobic biodegradation of coke wastewater in a two and three-step activated sludge process. *Journal of Hazardous Materials* **137** (3), 1681–1688.

Wei, X. X., Zhang, Z. Y., Fan, Q. L., Yuan, X. Y. & Guo, D. S. 2012 The effect of treatment stages on the coking wastewater hazardous compounds and their toxicity. *Journal of Hazardous Materials* **239**, 135–141.

Wieder, R. K. 1989 A survey of constructed wetlands for acid coal mine drainage treatment in the eastern United States. *Wetlands* **9** (2), 299–315.

WHO (World Health Organization) 1997 *Guidelines for Drinking Water Quality, 2nd edn., Vol. 2. Heath Criteria and Other Supporting Information*. World Health Organization, Geneva, Switzerland, pp. 940–949.

Yan, L., Wang, Y., Ma, H., Han, Z., Zhang, Q. & Chen, Y. 2012 Feasibility of fly ash-based composite coagulant for coal washing wastewater treatment. *Journal of Hazardous Materials* **203**, 221–228.

Yao, Z. T., Ji, X. S., Sarker, P. K., Tang, J. H., Ge, L. Q., Xia, M. S. & Xi, Y. Q. 2015 A comprehensive review on the applications of coal fly ash. *Earth-Science Reviews* **141**, 105–121.

Yu, X., Wei, C., Wu, H., Jiang, Z. & Xu, R. 2015 Improvement of biodegradability for coking wastewater by selective adsorption of hydrophobic organic pollutants. *Separation and Purification Technology* **151**, 23–30.

Yu, X., Xu, R., Wei, C. & Wu, H. 2016 Removal of cyanide compounds from coking wastewater by ferrous sulfate: improvement of biodegradability. *Journal of Hazardous Materials* **302**, 468–474.

Zhang, L., Zheng, P., Tang, C. & Jin, R. 2008 Anaerobic ammonium oxidation for treatment of ammonium-rich wastewaters. *Journal of Zhejiang University Science B* **9** (5), 416–426.

Zhang, T., Ding, L., Ren, H. & Xiong, X. 2009 Ammonium nitrogen removal from coking wastewater by chemical precipitation recycle technology. *Water Research* **43** (20), 5209–5215.

Zhang, M. h., lin Zhao, Q., Bai, X. & Fang Ye, Z. 2010 Adsorption of organic pollutants from coking wastewater by activated coke. *Colloids and Surfaces A* **362** (1), 140–146.

Zhao, W. T., Huang, X. & Lee, D. J. 2009 Enhanced treatment of coke plant wastewater using an anaerobic–anoxic–oxic membrane bioreactor system. *Separation and Purification Technology* **66** (2), 279–286.

Zhao, D., Lun, W. & Wei, J. 2017 Discussion on wastewater treatment process of coal chemical industry. In: *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 100(1), p. 012067.

Zhu, X., Ni, J. & Lai, P. 2009 Advanced treatment of biologically pretreated coking wastewater by electrochemical oxidation using boron-doped diamond electrodes. *Water Research* **43** (17), 4347–4355.

Ziemkiewicz, P. F., Skousen, J. G. & Simmons, J. 2003 Long-term performance of passive acid mine drainage treatment systems. *Mine Water and the Environment* **22** (3), 118–129.