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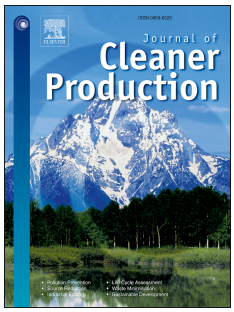

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The potential for the use of waste products from a variety of sectors in water treatment processes

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Abstract

This review examines the utilisation of waste products from three sectors (industry, agriculture, and construction and demolition) in filters for the removal of contaminants from water. Sand is commonly used in drinking water filtration in water treatment plants. However, the use of alternative, low-cost materials could address the limitations of sand, particularly for the removal of emerging contaminants, and address European legislation which fosters the development of a 'circular' economy, in which materials are used effectively. This review assesses the suitability of potential media by quantifying their adsorption potential across a variety of common drinking water contaminants. The media investigated were fly ash, Bayer residue, ground granular blast furnace slag, coconut shell, tea/coffee waste, rice husk, crushed concrete, masonry waste, and wood waste. There is a potential for the use of these media in the water treatment sector, although certain precautions must be taken to ensure any concerns are mitigated, such as release of metals into water. Recommendations, following this review, include testing the media in large-scale applications, and also constructing filters so as potential media are placed in layers to harness their contrasting adsorptive potentials.

Keywords: Media utilisation, water treatment, sustainability, cost-efficiency; filtration; review

1 Introduction

The European Union (EU) produces 2.3 billion tonnes of waste annually, of which 10% (or 250 million tonnes) includes municipal waste, and 90% includes industrial, commercial, agricultural, and other business related waste (Ruggiero, 2013). In agriculture, wastes are generated at production, post-harvest and processing stages (Parfitt et al., 2010), and amount to 1.3 billion tonnes per year worldwide (FAO, 2011). About 850 million tonnes of construction and demolition (C&D) waste is generated in the EU per year, representing 31% of the total waste generation in the EU (Fischer and Werge, 2009). However, the level of recycling and reuse of C&D waste varies greatly (between less than 10% to over 90%) across the EU. The concept of a 'zero waste' industry is not feasible, and while industries such as the C&D industry have a policy of reduction, reuse, recycle and disposal (Yuan and Shen, 2011), there is a tendency amongst stakeholders to only consider the use of wastes within the same sector (Duran et al., 2006), without considering their use in other sectors. One such avenue for the use of these wastes is in the water treatment sector, particularly as less than half the population of some countries in the developing world have access to clean, potable water (FAO, 2015), and as a need has been identified for cost-effective and robust solutions to improve water purification in both the developed and developing world (Shannon et al., 2008). Although drinking water improvement trends are increasing, in 2015, 663 million people were deprived of good quality drinking water, leaving much scope for improvements (WHO/UNICEF, 2015).

Improvements must include sophisticated strategies to combine water and energy savings, while striving for the ultimate goal of a circular economy (Bagatin et al., 2014). Although a 'zero-waste' society is not yet achievable, steps in this direction are continuing. Total recycling of

used products and an entirely circular economy may not be realistic in all scenarios, but it is possible to achieve a sustainable future by attempting to reach this goal (Reh, 2013). It is also important to maintain environmental and economic benefits while investigating material recovery concepts (Dahlbo et al., 2015), and so, either disposal or use post-treatment must also be considered to ensure a holistic design approach. It is also necessary to ensure new production processes do not create extra environmental impacts, which could even undermine those beneficial changes found by utilizing waste products (Mirabella et al., 2014).

Sand filtration is commonly used in drinking water purification. However, it can have shortfalls regarding the removal of certain contaminants (Water_Team, 2012). The use of a multi-layer filter containing a variety of media may have the potential to tackle problematic contaminants. Anthracite and coal are most commonly used in multi-layer filters, but these are costly and unsustainable adsorbents (EPA, 1995). The use of adsorption is evolving, as it produces satisfactory results while being cost-efficient and easy to design and operate (Bibi et al., 2015). The exploration of different adsorbents, both manufactured and recycled, is paving the way for a new generation of filters, containing a variety of media from many different sources (Bhatnagar and Sillanpää, 2010). The utilization of waste from sectors such as industry, agriculture and C&D as adsorbents allows for the development of sustainable and effective treatment technologies. The use of waste from certain processes could provide a more sustainable alternative for water treatment systems than abstraction of sand, for example by providing a use for an otherwise landfilled waste material.

There is increasing interest in the utilisation of waste materials, and there is a gap in knowledge in terms of the application to water treatment processes. This paper investigates a variety of media from three sectors (industry, agriculture and C&D) that could be used in filters for the removal of contaminants from water.

1.1 Adsorption classification and contaminant definitions

The potential adsorption capacity of media can be classified mathematically using a number of adsorption isotherm models (Foo and Hameed 2010), allowing for a comparison between the theoretical adsorption capacity of novel versus traditional media. In turn, these data would allow the relative efficacy of one type of filter media over another to be evaluated. There has been considerable research into the adsorption capacities of a huge variety of media to adsorb a variety of contaminants, such as clays, zeolites and chitosan for nitrate removal (Bhatnagar and Sillanpää, 2011), carbon nanotubes, biosorbents and low cost adsorbents for heavy metal removal (Fu and Wang, 2011), and agricultural wastes for water purification (Bhatnagar et al., 2015). However, for the purposes of this review, common drinking water contaminants will be investigated against a selection of media arising from industrial, C&D, and agricultural sectors.

The legislation discussed in the current review is Irish drinking water legislation (SI No 278 of 2007, 2007); however, this is based on the European Communities (Drinking Water) (No 2) Regulations 2007. Discrepancies between these and United States regulations, where they arise, are stated in the current paper. The European Communities set out clear quality standards for water for human consumption. A total of 39 parameters must be tested for on a regular basis, and 95% of samples must comply with the regulations. There are further requirements for those

samples which do not pass. To allow for a broad overview of media and contaminants, a small selection has been chosen on which the review is based.

Phosphorus (P) is not currently legislated for under drinking water quality legislation. However, given that most potable water uses surface- or ground-water as its abstraction source, P is likely to be found in abstraction water. The Water Framework Directive (2000/60/EC; EC, 2000) states the threshold level of P in water to be 0.035 mg L^{-1}. However there is a likelihood that certain locations in the EU will not meet this objective, based on current trends (EPA, 2015a). Phosphorus causes detrimental eutrophication effects when present in surface water sources, and can have negative effects following human consumption. Phosphorus is also likely to cause problems in the water distribution network, with excessive amounts increasing microbial growth (Miettinen et al., 1997).

Nitrogen (N) can be present in water as ammonium (NH_4^+-N), nitrate (NO_3^--N) and nitrite-N (NO_2^--N) and organic nitrogen. The maximum allowable concentration (MAC) for NH_4^+-N in drinking water is 0.3 mg L^{-1}. The presence of NH_4^+-N in water treatment plants can have a negative impact on (i) disinfection by resulting in increased chlorine consumption or reducing the effect of chlorine-based disinfection systems (Wilczak et al., 1996) and (ii) both pH and dissolved oxygen (DO) in the distribution system (Feng et al., 2012). The MAC for NO_3^--N in drinking water is 11 mg L^{-1}. Nitrate can enter drinking water abstraction sources from anthropogenic sources, generally from municipal wastewater treatment plants where denitrification was incomplete, and from agricultural land (Bagatin et al., 2014). The MAC for NO_2^--N in drinking water is 0.5 mg L^{-1}, and its presence has also been linked to blue-baby syndrome (Fan and Steinberg, 1996). Nitrogen is most

commonly removed at filtration stage by a combination of biological and chemical removal mechanisms, with the biological activity occurring at the surface of the filters.

There is no MAC for dissolved organic carbon (DOC), with legislation stating “no abnormal change” must be observed. However, the presence of organic carbon in water can, following disinfection, result in the formation of multiple disinfection by-products (DBP) (EPA, 2012). Total trihalomethanes (TTHM) are the most commonly occurring disinfection by-products, and are the only ones regulated by legislation, with a MAC of TTHM in Ireland of 0.1 mg L^{-1} (SI No 278 of 2007, 2007) and in the United States of 0.08 mg L^{-1} (USEPA, 2009). Disinfection by-products are carcinogenic and have been linked to reproductive issues and birth defects (Richardson, 2003). The composition of DOC has an impact on the formation potential of DBP, with the hydrophobic fraction, comprising mainly humic substances, most likely to form DBP (Tran et al., 2015). Humic acid is a constituent of natural organic matter in surface and ground water sources, and is often used in adsorption studies. The potential formation will also differ depending on temperature, rainfall, pH, alkalinity, surrounding soils, and time of year (EPA, 2012). For the purposes of this paper, the focus is on DOC adsorption, rather than the by-products.

Metals are most likely to enter drinking water abstraction sources by anthropogenic sources, such as mining, drainage, corrosion of pipes (EPA, 2015b), and by industrial processes (Mohod and Dhote, 2013). In legislation, each metal has a different MAC, depending on the severity of the effects on human health. For example, the MAC of aluminium (Al) is 200 µg L^{-1}, chromium (Cr) is 50 µg L^{-1}, copper (Cu) is 2 mg L^{-1}, lead (Pb) is 10 µg L^{-1}, and iron (Fe) is 200 µg L^{-1}. The presence of metals in water can be associated with many physiological illnesses attacking the major organs of the human body (Mohod and Dhote, 2013).

Although adsorption of individual contaminants onto various media is well examined in the literature, reviews tend to group the literature based on a single contaminant or in terms of wastewater treatment, and often investigates commercial adsorbents. This review focuses on a variety of drinking water contaminants, solely from the point-of-view of reusing by-products or waste material, and it provides researchers and practitioners with a comprehensive overview on a number of different materials. This would not only allow for improved water treatment, but also improvements for the environment as a whole, by aiming to reduce waste products and disposal of same.

2 Methodology

A detailed literature search was carried out by initially selecting several key words. Those used include: adsorption, waste products, waste reuse, water treatment, regeneration, agricultural-based adsorbents, construction-based adsorbents, and industrial-based adsorbents. Each media mentioned was also included in a search. The search was limited to papers published in the last ten years, where possible. Exceptions were made for highly cited papers and areas where there was limited research available. No geographical limitations were applied. Search engines used included databases such as Scopus, as well as publisher-specific search engines such as ScienceDirect, Royal Society of Chemistry, American Chemical Society, and Materials Research Society, and the Boolean operator “AND” was used to include several keywords in one search. References from selected papers were also explored for relevant information.

Articles were selected based on relevance to the review, with a focus on the selected media from industry, agriculture, and construction and demolition sectors. Particular attention was paid to those contaminants of concern, although all adsorption studies were considered for inclusion.

Post-treatment use and regeneration were also considered when selecting articles. A total of 210 references were selected, of which most are journal papers from chemistry, engineering, and material science research areas. A small number of books and reports were also included.

3 Industrial waste

Industrial activities generate products and residues from both production and consumption. As industrial activity continues to increase, so too does the creation of excessive waste. In 2012, 48% of total waste in the EU was disposed, and the remainder was either recycled, or used for energy recovery, backfilling or incineration (Eurostat, 2015). The utilisation of industrial by-products and wastes in water treatment is infrequently examined in the literature. The wastes that will be considered in this paper are fly ash and ground granular blast furnace slag (GGBS), and Bayer residue. Fly ash was chosen as it comprises 85% of all ash produced in coal combustion products (CCP), with approximately 780 million tonnes produced worldwide (Heidrich et al., 2013). Ground granular blast furnace slag was chosen as it is a product of over 1 billion tonnes of steel produced (Juckes, 2011), and Bayer residue because of the increasing accumulation of the waste (EAA, 2013).

3.1 Fly ash

Fly ash (specifically coal fly ash) is a waste product of the incineration process. It is defined as a non-hazardous mineral combustion waste, with coal fly ash falling under the category of slags and ashes from thermal treatment combustion (Eurostat, 2010). It has a recognised potential use as a raw/construction material in applications such as cement and concrete addition (ESB Moneypoint, 2012), with more than half of the concrete used in the USA containing fly ash (World Coal Association, 2015). The current utilisation rate for fly ash use in the EU is approximately 43%, leaving over 17 million tonnes for disposal or stockpiling (Ecoba, 2015).

Fly ash is produced by the incineration process when coal is burned as a power source, and in incineration of municipal solid wastes, sugar cane bagasse, rice husks and tea dusts. For many years production has exceeded utilisation capabilities, meaning a large proportion is landfilled (Ecoba, 2015). For the purposes of this review, power station fly ash (coal combustion) is of most interest, as it is the largest source of fly ash production (Iyer and Scott 2001). The major components are silica, Al, Fe oxides, carbon, calcium (Ca), magnesium (Mg), and sulphur in varying amounts, depending on the original source (Iyer and Scott 2001). Chemical characteristics are detailed in Table 10. With such a large variety of elements, fly ash has potential for many uses (Figure 3), and efforts should be made to avoid landfilling.

3.1.1 Current Uses

In the construction industry, fly ash is mostly used in concrete addition (35.9% of total use of fly ash in 2010), with other uses including blended cement, road construction and concrete blocks (Ecoba, 2015). Research has been carried out on increasing the amount of fly ash in certain concrete mixtures to increase performance (Mehta, 2002). This must be cautioned however, as fly ash can adsorb concrete surfactants which may have negative effects on the mixture (Ahmed and Hand, 2014). The fine nature and elemental composition of fly ash has led to investigations into the use of fly ash as a fertiliser (Jala and Goyal, 2006) and for soil conditioning, which has demonstrated positive results on a short-term basis (Kalra et al., 1998), though this should only be used where the fly ash will not compromise the soil quality (Pandey and Singh, 2010).

3.1.2 Potential for use in water treatment

Fly ash has been well recognised for its efficacy as an adsorptive material for various contaminants in aqueous solutions (Ahmaruzzaman, 2010). Table 11 gives an overview of the adsorption potential, based on adsorption isotherm modelling, targeting in particular those contaminants of interest in this review. Fly ash also has the ability to uptake metals, such as Pb and Cu (Alinnor, 2007), and zinc (Zn) and manganese (Nascimento et al., 2009) from aqueous solutions, and its capacity may be improved by the presence of humic acid in water (Wang, et al., 2008a). Metal removal using fly ash can also be enhanced by coating with chitosan (Adamczuk and Kołodyńska, 2015). Lignin removal can be achieved by fly ash (Andersson et al., 2011), as can phenanthrene (An and Huang, 2012). Little research has been carried out on NH_4^+-N adsorption, other than cation exchange capacity (CEC) investigations with synthesised zeolite from fly ash.

Many studies have been carried out to investigate the efficacy of zeolite that is synthesised from fly ash (ZFA), for example to remove heavy metals from wastewater (Querol et al., 2002), phosphate from an aqueous solution (Chen et al., 2006), and for humic acid removal from water (Li et al., 2011). Synthetic zeolites from fly ash have been shown to have a CEC of up to 3 meq g^{-1}, allowing for the uptake of heavy metals and cations such as NH_4^+-N (Querol et al., 2002). Wu et al. (2006) investigated the increase of CEC of ZFA by salt treatment, and simultaneous P and NH_4^+-N removal, which was particularly effective at low concentrations. A mild acid treatment has been shown to have a similar effect on ZFA (Zhang et al., 2007).

The main disadvantage to using fly ash in water treatment is the potential for metal leaching. By its nature, metals are an intrinsic characteristic of fly ash (Chou et al., 2009). However, with the introduction of some precautionary measures, where necessary, this can be mitigated. Measures

may include a leaching behaviour test (for example, where systems may contain other adsorptive media), forced extraction, immobilisation of elements, and destruction of persistent pollutants (Wang and Wu 2006).

Acid, heat, and activation all have a positive effect on the adsorption capacity of fly ash (Li et al., 2006). However, for the most sustainable and cost-effective approach, the raw state is generally stated to be most desirable (Alinnor, 2007). Phosphorus and humic acid can also be successfully removed from water (Table 11) using fly ash. However, there is little investigation of co-adsorption and contaminant interaction. Wang et al. (2008a) studied the positive effect of humic acid presence on metal adsorption, but to comprehensively assess the potential for the use of fly ash in a sustainable technology, it is necessary to study the raw water contaminants in a combined and natural environment.

3.2 Ground granulated blast furnace slag

Ground granular blast furnace slag is a waste product of the steel production industry. It is non-hazardous, and is a finely ground powder. Similar to fly ash, GGBS falls under the category of mineral combustion wastes, and is hazardous if it contains toxic heavy metals (Eurostat, 2013). Over a billion tonnes of steel is manufactured per annum, leading to the availability of a large amount of GGBS (Juckes, 2011).

Ground granulated blast furnace slag is produced from blast furnaces used in Fe production. Molten slag is produced when iron-ore, coke and limestone are melted in a blast furnace. Slag floats on the molten iron, and once removed, is granulated and ground to produce GGBS (Siddique and Bennacer, 2012). Ground granulated blast furnace slag typically contains oxides of calcium, silica, Al and Mg in varying proportions (Ecocem, 2012).

3.2.1 Current Uses

In Europe, almost 18 million tonnes of GGBS is currently used in the cement and concrete industries (Ecocem, 2015). This is the most common use for GGBS. It acts as a direct replacement for cement, and has many advantages including extending the life cycle of concrete, making concrete more durable, and reducing the carbon and energy footprint of concrete production (Ecocem, 2015). Blended cements (GGBS and ordinary Portland cement) have a superior resistance to sulphates and an increased chloride binding capacity (Siddique and Bennacer, 2012).

3.2.2 Potential for use in water treatment

Ground granulated blast furnace slag has not been previously identified as an adsorptive material, and little research has been carried out in this regard. The chemical composition of GGBS would indicate potential for a strong CEC for cation and metal adsorptions. Grace et al. (2015) found that GBS (granular blast furnace slag) had good adsorption properties but solidified upon immersing in water, which would counteract the usefulness in a water treatment system. Further research is necessary to investigate pre-treatments which would allow the adsorption potential of GGBS to be harnessed and utilised.

3.3 Bayer residue

Bayer residue (also called bauxite residue or red mud) is a primary waste product of the Al production industry. Accumulation of the residue is estimated to be increasing by 110 million tonnes per annum, with 2700 million tonnes already in storage in 2010 (EAA, 2013). Bayer residue is highly alkaline and has a fine particle size, leading to environmental issues around disposal and storage.

Aluminium is most often refined from bauxite ore, which is readily available all over the world. The ore contains high levels of Al oxides, which can be extracted by the Bayer process. This involves heating the bauxite in caustic soda under high temperature and pressure, to form sodium aluminate and an insoluble residue - known as Bayer residue (Deelwal et al., 2014). The sodium aluminate is further treated to form Al hydroxide or oxide. The Bayer residue typically contains Fe oxide, Al oxide, titanium oxide, calcium oxide, silica oxide and sodium oxide (EAA, 2013).

3.3.1 Current Uses

Bayer residue is stored at or close to the alumina manufacturing facility in a bauxite residue storage area or in dry stacking facilities (Nikraz et al., 2007). Bauxite residue storage areas should be carefully controlled, with hydrosphere monitoring to avoid any negative environmental or ecological impacts (EAA, 2013). It is a concerning issue for many nations; indeed the Chinese government set a target of utilising 20% of fresh mud by the end of 2015 (Liu et al., 2014). Approximately 110 million tonnes of Bayer residue are produced and stored worldwide annually (EAA, 2013), and amount currently in storage is expected to increase to 4 billion tonnes by 2015 (Liu and Naidu, 2014). Therefore, it is the subject of ongoing research to identify potential uses and alternative disposal mechanisms such as soil amelioration, construction and groundworks restoration (EAA, 2013). Work has been carried out on the use of Bayer residue as a construction additive or filling material (Deelwal et al., 2014). Limited work has been carried out on the use of Bayer residue as a coagulant or as an industrial catalyst, showing it may have potential in this area (Wang, et al., 2008b), for example to purify a bio-diesel waste stream (Resende et al., 2013). Work has also been carried out on iron recovery from Bayer residue (Liu and Naidu, 2014).

3.3.2 Potential for use in water treatment

Previous studies indicate that Bayer residue has potential as an adsorptive material for removal of contaminants from water supplies, and it has been suggested that exhausted material be re-used in the construction sector (Ali and Gupta, 2006). Metal removal from aqueous solution has been examined successfully (Hua et al., 2014), although further work is required to understand the removal techniques and consequences (Brunori et al., 2005). Phosphorus removal is very effective using Bayer residue (Table 12Table 12), and limited studies of NO_3^--N, along with other anion adsorption studies (Bhatnagar et al., 2011), have produced positive results. Gaps exist in the adsorption potential of NH_4^+-N and DOC, although Lopez et al. (1998) observed NH_4^+-N removal from secondary effluent from a wastewater treatment plant. Bayer residue can also achieve more than 90% bromate removal from aqueous solutions (Chen et al., 2016). The positive results indicate that further research should be carried out to assess the removal capabilities of a spectrum of contaminants.

The most relevant disadvantage to using Bayer residue in water treatment processes is reflected in environmental concerns (Liu et al., 2011). Its chemical and mineralogical characteristics require treatment before storage and it is important to ensure it does not further pollute water or leach contaminants. The adsorption potential may outweigh the concerns, and carefully designed systems could mitigate any possible concerns.

4 Agricultural waste

The agricultural sector is constantly growing, particularly as trade relations strengthen between countries and demographics continue to put pressure on food production systems. Thirty-eight percent of the EU budget is spent on agriculture, with exports steadily rising and currently estimated to have a value of €122 billion (European Commission, 2015a). Globally, trade flow values have increased fivefold in the past 50

years (United Nations, 2015). Twelve percent of the total land area of the world is used for crop production in the agricultural sector (United Nations, 2015). This produces many different types of wastes and by-products. In this review, those examined are coconut shell, tea and coffee wastes, and rice husk.

4.1 Coconut Shell

Coconut shell is frequently used as a carbonaceous source for activated carbon, as it results in a strong, dense carbon (Cooney, 1999). Although powdered coconut shell can be used for adsorption, the most common use is as an activated carbon source. This is a successful adsorbent, but the activation process can be expensive, and using the raw material as is would be a more sustainable approach.

Activated carbon is manufactured in a two-step process. First, raw materials go under a carbonization process in an inert environment, and then the carbonized product is activated with oxidising gases (Hu and Srinivasan, 1999). The oxidation process erodes a network of internal channels and pores, while creating a surface of oxides, to increase the surface area and make the material more suitable for adsorption (Cooney, 1999).

4.1.1 Current Uses

In developing countries, coconut shells have practical uses such as bowls and utensils, but the most common large-scale use for coconut shell is the production of activated carbon. More than 61 million tonnes of coconuts are grown worldwide annually, most commonly used for drinking, coconut oil, and dessicated coconut (UNCTAD, 2012). This volume of raw material gives much scope for activated carbon production. Coconut

shells have also been used in construction, to create coconut shell aggregate concrete; however, this is not commonly used (Gunasekaran et al., 2012).

4.1.2 Potential for use in water treatment

Table 13 presents a selection of previous studies investigating adsorption using coconut shell in terms of relevant contaminants for drinking water treatment. Coconut-based adsorbents are well studied in terms of biosorption for water treatment. Bhatnagar et al. (2010) reviewed a variety of coconut biosorbents for removal of metals, dyes, pollutants, anions and radionuclides from water, concluding that the potential for use is great, although knowledge gaps still exist in terms of real effluent use, regeneration and recovery studies.

Coconut shell has been successfully used in adsorption of metals such as Cu, Pb, cadmium (Cd) and Zn (Sousa et al., 2010), and dye adsorption (Cazetta et al., 2011), various anions such as those mentioned in Table 13, and fluoride (Sathish et al., 2007). Nickel can also be adsorbed using coconut shell (Vocciante et al., 2014). Adsorption of dyes can be indicative of an adsorbent's affinity to adsorb various molecular weights of organic matter (Zhang et al., 2007), thus activated carbon from coconut shell has good potential to adsorb natural organic matter (NOM). Studies have shown that the presence of NOM in aqueous solutions can inhibit or at least compete with adsorption of other trace organic compounds that are commonly found in drinking water by pore blockage and site competition (Quinlivan et al., 2005).

Evidence suggests that coconut shell-derived activated carbon is useful in terms of water treatment. However, the carbonization and activation process can be expensive and technology-intensive, meaning that it is not as sustainable as other by-products. It is also likely to become

saturated and exhausted, requiring a regeneration treatment. Coconut shell could be combined with another adsorbent to reduce the need for regeneration yet achieve effective and sustainable water treatment.

4.2 Tea/Coffee wastes

Worldwide coffee and tea production is a large industry, with the total coffee production per crop year 2014/15 at 141.7 million 60 kg bags (ICO, 2015) and world tea crop production in 2013 was 5.3 million tonnes (FAOSTAT, 2015). The chemical composition of tea varies depending on the type, but the largest proportion generally comprises polyphenols, as well as sugars, some amino acids, lipids and some minerals (Harbowy et al., 1997). Similarly, coffee varies depending on the type, but major constituents are fatty acids, hydrocarbons and sterols (Pujol et al., 2013).

4.2.1 Current Uses

Coffee and tea grounds/leaves are most commonly disposed of in compost or in landfill disposal. Coffee grains can be beneficial for vermi-composting, by allowing the kitchen waste to become more stable for earthworm populations (Adi and Noor, 2009). Biofuel production has also proved successful with coffee grains (Caetano et al., 2014). However, if a potential use is identified, it would reduce the need for landfill. Studies have also been carried out to investigate the preparation of activated carbon from these wastes by pyrolysis (Reffas et al., 2010) and acid impregnation for improved adsorption of dyes (Ma and Ouyang, 2013).

4.2.2 Potential for use in water treatment

Coffee grounds (Safarik et al., 2012) and tea grains have been used successfully in dye adsorption (Nasuha et al., 2010), which can be used to indicate a potential for use in cationic adsorption requirements (Franca et al., 2009). Metal removal has been achieved using both coffee grounds and tea leaf wastes (Djati Utomo and Hunter, 2010). Phenol removal has also been successful with activated carbon prepared from coffee residue (Lamine et al., 2014). Wang et al. (2014) reported a NO_3^--N removal efficiency of almost 52% using green tea extract.

The above evidence would suggest that there is scope for tea and coffee wastes to be used in a technology for water treatment, particularly for adsorption of cationic compounds; however, further analysis is required on nutrient and carbon adsorption to fully understand the benefits.

4.3 Rice husk

Rice husks (hulls) are the outer covering on the grain, separated from rice during milling. In Asia, 700 million tonnes of rice husk are produced annually (Santiaguel, 2013), accounting for 92% of the worldwide rice production (Ricehusk.com, 2015). The chemical composition of rice husk includes cellulose, hemicellulose, lignin, silica, ash, and protein (Krishnani et al., 2008).

4.3.1 Current Uses

Rice husk was generally considered a waste product, but in recent years, it has become a commodity, and has uses such as power production (from biomass gasification) and a raw material for chopstick manufacture (Santiaguel, 2013). It can also be used in horticulture, animal bedding,

and as a material in composites (Ricehusk.com, 2015). Thermal treatment of the husk can aid in oil (Angelova et al., 2011) and petroleum adsorption (Kenes et al., 2012).

When rice husk is burnt, it produces an ash, with a high silica content, that can be used in concrete production and insulation products (Singhania, 2004). The ash has also been used in purification methods, such as the preparation of biodiesel from frying oil (Manique et al., 2012). Similarly, oil polluted water can be cleaned using the ash (Vlaev et al., 2011).

4.3.2 Potential for use in water treatment

From various studies and reviews, it is clear that rice husk is a successful adsorbent (Ahmaruzzaman and Gupta, 2011). K: Freundlich adsorption capacity factor

Table 14 K: Freundlich adsorption capacity factor

Table 14 details the previous adsorption studies of the contaminants examined in this review, indicating that rice husk can be used in a treatment technology.

Rice husk has proven to adsorb metals from wastewater successfully, particularly when used as a starting material for activated carbon preparation (Daifullah et al., 2003). A partial alkali digestion of rice husk also improved the metal binding ability, showing a good affinity for eight different heavy metals (Krishnani et al., 2008). Mohan and Sreelakshmi (2008) found that treating rice husk with P increased its affinity for metal adsorption. Other studies confirm the affinity of rice husk for adsorption of metals such as Cd (Ye et al., 2010), nickel and Zn (Srivastava et al., 2007), and Pb and mercury (Feng et al., 2004), and also for dye adsorption (Kumar et al., 2014). Rice husk ash can also be used as a precursor to activated carbon, which has been successful for dye removal (Liu et al., 2012).

To further assess the potential of using rice husk in a water treatment technology, it is necessary to compare the advantages to its current uses, to ensure it is a viable adsorption source. It is also necessary to assess the cost of having to modify the husk, compared to using a raw, untreated material.

5 Construction and demolition waste

Construction and demolition wastes encompass a wide variety of media, from wood, metals and plastics, to textiles and paper, oils and minerals (Eurostat, 2013). Figure 4 shows the composition of C&D wastes, for EU member states, excluding Estonia and Finland (European Commission, 2011). Large quantities of C&D waste is produced every year and it accounts for 25-30% of all waste in the EU (European Commission, 2015b). Although recycling efforts are substantial (greater than 50%), there is still a necessity for further re-use of some of this material (Fischer and Werge, 2009). In 2012 in Europe, 40 million tonnes, of

a total 295 million tonnes, of mineral waste from C&D was deposited onto or into land, meaning there is a large quantity of potential mineral waste available (Eurostat, 2015). This will allow for compliance with the EU Waste Framework Directive (2008/98/EC; EC, 2008), which states that recycling efforts must be raised to at least 70% (Fischer and Werge, 2009). To aid in reaching this target, it is necessary to examine the potential for certain C&D wastes for other purposes, such as water and wastewater treatment. The wastes of interest in this review are crushed concrete, masonry waste and wood waste.

5.1 Crushed Concrete

Crushed concrete is a waste product from the C&D industry, resulting from the demolition of buildings and concrete structures. Crushed concrete comprises the largest fraction of C&D waste (Figure 4), so finding an alternative use is extremely important. It comprises the standard components of a concrete mixture, aggregates, water, cement and sand. This results in a chemical composition of Ca oxides, Al oxides and Fe oxides (Egemose et al., 2012).

Production of crushed concrete arises from the need to reduce landfill waste from all industries, including the C&D industry, with crushing meaning it is more suitable for use elsewhere. Debris and rubble from buildings that have been damaged in destructive earthquakes, along with regeneration demolition, and rebuilding roads and runways result in large amounts of waste. The debris is crushed and ground using various techniques dependent on the required use (Topçu and Şengel, 2004).

5.1.1 Current Uses

A certain amount of old concrete from the C&D sector still goes to landfill. Crushed concrete can be reused as a form of aggregate; however, this must be done with caution, as increasing amounts of waste concrete aggregate can decrease density, workability, hardness and compressive strength (Topçu, 1997).

5.1.2 Potential for use in water treatment

Table 15 details previous work on adsorption studies using crushed concrete. Egemose et al. (2012) investigated the use of crushed concrete as a filter material for urban and agricultural runoff. The study found that it was effective in P removal, but observed that caution must be taken to ensure the pH and alkalinity of the effluent is controlled. During a column study to treat secondary effluent wastewater from a municipal wastewater treatment plant, Berg et al. (2005) discovered that although crushed gas concrete (lightweight concrete) was effective at reducing the concentration of P by 80-100%, the DOC was unchanged, meaning crushed concrete may not be effective as a stand-alone filter media, depending on the contaminants in question. Crushed concrete has shown potential for metal adsorption, with successful adsorption of Cu, Zn and Pb (Coleman et al., 2005). There are indications that crushed concrete may be a successful filter media for removal of contaminants from aqueous solutions, but further work would have to be carried out across a broad spectrum of contaminants to fully assess its potential.

5.2 Masonry

Masonry waste comprises a large proportion of the C&D waste generated in the EU (Figure 4), approximately 30%, and is classified under the same waste stream as concrete and gypsum-based materials. It refers to a mixed waste comprising bricks, tiles and ceramics, and any other masonry rubble; and can arise from construction of civil infrastructure, or from demolition (European Commission, 1999). The properties of masonry, both physical and chemical, vary depending on the proportions of the components present in any one sample (del Rio Merino et al., 2010). It can also vary depending on location, given that different regions may use different types of bricks. In some countries, such as Pakistan, brick powder is readily available and may have few costs associated with its use (Bibi et al., 2015). In

general, it comprises silicate minerals, rich in silicon, Al oxides and hydroxides (Naceri and Hamina, 2009).

5.2.1 Current Uses

Masonry waste from the C&D industry can be reused in the same industry, particularly as aggregate for concrete production, mortars, roof elements, concrete blocks and concrete tiles (del Rio Merino et al., 2010). There have also been studies carried out to investigate the use of masonry waste as a replacement of clinker in cement (Naceri and Hamina, 2009), and as a pozzolonic admixture (Lavat et al., 2009).

5.2.2 Potential for use in water treatment

Table 16 details the studies which have investigated those contaminants of interest in this review. Crushed brick has been used to remove dye from aqueous solutions effectively (Hamdaoui, 2006). Metals, such as Cu (Djeribi and Hamdaoui, 2008) and mercury (Labidi, 2008), have also been removed from aqueous solutions using crushed brick. Brick has also been used for microbiological adsorption, with *Clostridium beijerinckii* found to adsorb onto the surface (Qureshi et al., 2000). Ceramics have also been used in contaminant removal from aqueous solutions. Fluoride has been successfully adsorbed by granular ceramic (Chen et al., 2011), and silica ceramic has been used to remove arsenic from aqueous solution (Salim and Munekage 2009). Brick powder has also been successfully used for both fluoride and arsenic removal (Bibi et al., 2015).

It is clear that there is potential in the use of masonry waste as an adsorbent for water treatment. With the ability to adsorb such a variety of contaminants, the next step would be to assess its potential to adsorb multiple contaminants simultaneously. The biggest disadvantage, however, is the lack of uniformity. Depending on the source, the masonry waste composition could have a huge variance, which will in turn affect the potential for use.

5.3 Wood waste

Although wood waste only accounts for 2% of the EU C&D waste (Figure 4), it is a relevant waste to investigate, given that in certain countries this figure may be higher. For example, in Ireland, in 2010, wood accounted for 5% of total C&D waste collected, amounting to 45,000 tonnes (EPA, 2010). Wood waste can arise from discarded treated and untreated wood products, off-cuts, shavings, chip and dust from wood processing and virgin wood mixed in with waste wood (EPA, 2013). The composition of wood varies depending on the source of the timber. It is imperative to encourage the use of wood in a material recovery sense, as currently a significant proportion is used in energy (Dahlbo et al., 2015).

5.3.1 Current Uses

Waste wood has many different uses, including fuel, landscaping, bedding, composite boarding manufacture, landfill cover and composting. It can be used both as biofuel and as a fuel in its raw state (Lippke et al., 2012). However, the use of waste wood as fuel brings environmental concerns, given the likelihood of halogenated organic compounds or heavy metals to be present, following preservation methods (EPA, 2013).

5.3.2 Potential for use in water treatment

Wood waste, in the form of wood chips, has been successfully used in adsorption of dye from aqueous solutions (Nigam et al., 2000). Sawdust has been successfully used in the same way (Hanafiah et al., 2012). Wood also has good capacities for metal adsorption (Rafatullah et al., 2012). Alternative methods for using wood waste in water treatment would be as a biochar, for nutrient (Wang et al., 2015), perchlorate (Fang et al., 2014), or metal adsorption (Jiang et al., 2015); or as an activated carbon, for dye (Ma et al., 2014) and metal adsorption (Lo et al., 2012). Table 17 details adsorption studies that have been carried out using relevant contaminants, mainly in the form of biochar adsorption, indicating that there is a possibility of using this material, though further research should be carried out.

122 It is clear that waste wood does have potential for use in water treatment. However, there will
123 be a lot of variability depending on the original type of wood used. Another issue could be
124 the release of organics into the water. To avoid a release, a pre-treatment could be advised
125 and perhaps the use of a multi-media technology to harness different sorption capacities.

126 **6 Post-treatment use of media**

127 It is clear from the review of previous studies that the scope for alternative media use as
128 adsorbents in water treatment is broad, encompassing many types of media and contaminants.
129 However, a problem still remains with disposal of the media post-treatment. The recycling of
130 waste does often create larger environmental benefits, particularly than energy recovery
131 methods, but this is not always the case and should be carefully analysed (Dahlbo et al.,
132 2015). Although adsorption can create a purpose for an otherwise discarded material,
133 adsorption is not an infinite solution. Once used in an adsorption system in water treatment, it
134 will be necessary to either regenerate or find a safe disposal mechanism for the media. This
135 will also ensure any contaminants adsorbed onto the media will not pollute land or water.

136 The use of the media post-treatment depends on the constituents of the water it was used to
137 treat. If the raw water contained heavy metals, it is necessary to ensure that metals would not
138 pose a threat to the next purpose of the media. In the case of adsorption of organic pollutants,
139 successful regeneration and desorption techniques, such as biological degradation, chemical
140 desorption, oxidation, and thermal desorption, may be used to restore the quality of the media
141 (Zhu et al., 2009). Where nutrients are problematic contaminants, land fertilisation may be a
142 potential area of utilisation post-treatment. This would be doubly beneficial as it would
143 improve the land quality and provide a useful purpose for what is otherwise a waste material.

6.1 Regeneration

It is recognised that there exists a knowledge gap on large-scale regeneration of adsorbents, particularly non-carbonaceous adsorbents (Omorogie et al., 2014). Traditional regeneration techniques include thermal, chemical, and bioregeneration. Emerging regeneration techniques include electrochemical, ultrasound, oxidation, and supercritical fluid methods (Duan et al., 2013). Although many of these techniques have proved effective, it is necessary to implement large-scale regeneration of media, for both economic and environmental benefits (Omorogie et al., 2014).

Regeneration of metal oxides, such as fly ash and Bayer residue, has not been extensively studied. The studies which have been carried out tend to refer to treated media, such as impregnated fly ash (Yang et al., 2016) or activated carbon prepared from fly ash (Aslam et al., 2015). However, it has been found that where these media have been used to adsorb various metals, it can make the media more stable (Jacukowicz-Sobala et al., 2015). It has also been shown that methods such as thermal desorption can be used to restore the media to its previous condition (Yang et al., 2016). This can result in the media being used for land reclamation, or in construction methods such as those mentioned in the “current uses” sections above. Fly ash, once exhausted from certain adsorbents, can be used as a filler in paper-making with few side-effects (Saakshy et al., 2015). Although similar studies have not been carried out in relation to GGBS, the chemical composition would suggest similar potential. The United States Environmental Protection Agency (USEPA) have developed a number of tests which can be used to investigate the potential leaching and toxicity of spent sorption material and suitability for use on land (Jacukowicz-Sobala et al., 2015).

Regeneration of coconut shell activated carbon is well researched, with up to five adsorption-regeneration cycles being tested. For adsorption of gaseous sulphur, complete regeneration can be achieved using water vapour (Shi et al., 2015). Microwave regeneration was not as

effective when used to regenerate from benzene and toluene adsorption, achieving just 50% removal efficiency after five cycles (Mohammed et al., 2015). Thermal regeneration with 0.1M NaOH was very effective for regeneration from Pb removal, with removal efficiencies of over 90% after cycling (Itodo et al., 2014). Other activated carbons have been regenerated successfully by electrical-assisted acid washing (Weng et al., 2014), supercritical carbon dioxide operating conditions (Carmona et al., 2014), and pyrite-activated sodium persulfate oxidation (Liang and Chen, 2010).

Similar to the other agricultural wastes, several regeneration techniques have proved successful for both tea wastes (Fadhil et al., 2012) and coffee wastes (Plaza et al., 2012). These wastes can be used as a source material for activated carbon and so respond well to regeneration. Although regeneration can still mean the pollutant is present, it becomes concentrated, and thus may be more easily disposed of (Kyzas, 2012), while the material can be returned to its original state. Alternative disposal mechanisms include manufacturing blended fuel briquettes from tea and coffee wastes, due to high calorific values (Nandal et al., 2014).

Bioregeneration has successfully been used for rice husk regeneration (Aktas and Cecen, 2007), as have chemical techniques. Chemically modified rice husk for mercury adsorption was successfully regenerated using 0.1M HCl, only losing 10% adsorption capacity (Song et al., 2016). Regeneration by NaOH has been successfully used for rice husk that has been used for arsenate (Luo et al., 2016) and Pb adsorption (Masoumi et al., 2016). Rice husk ash, a product of the incineration of rice husk, has many uses including catalyst carriers, fillers in cement, fertilisers, and production of gels and polymers (Kumar et al., 2016). This would be a useful post-treatment use of rice husk, provided that the contaminants would be contained and not leached to the environment.

Construction and demolition wastes are not well researched in terms of regeneration processes. Where an activated carbon was produced from wood waste, regeneration would be most likely successful. For concrete and masonry, depending on the source water contaminants, there is potential for use as aggregate or fill in the construction industry. However, extensive testing would be necessary to ensure no damage would occur to the environment.

6.2 Economic and environmental outlook

When considering regeneration techniques, it is important to recognise the economic and environmental costs of regeneration techniques. Where acid regeneration is used, it can be corrosive and difficult to store. Thermal regeneration techniques can require complex instrumentation and large capital expenditure (Aslam et al., 2015). Regeneration can also produce a high concentrate waste stream, which can bring about further issues of waste management (Igunnu and Chen, 2012). Therefore, it is important to analyse filter media holistically, including potential regeneration and costs, to ensure the most sustainable approach is taken.

It is important ensure that the use of the media in water treatment does not devalue the original product. Desorption techniques may be used to restore the product, although it may create another issue regarding waste creation as the pollutant will now be concentrated. In some instances, the original product may become more stable, and may still be useful in its current uses. In other cases, for example when used for nutrient capture, the media may then be used as a fertiliser. The ultimate use of the media will depend on the raw water being treated, and how that impacts on the media. However, it is clear that this is an area worth researching with clear gaps in knowledge evident.

The notion of a 'circular economy' requires products, materials, and services to be maintained within the economy for as long as possible, and is a major step towards a zero-waste society (European Commission, 2015c). Although the utilisation of these products does not result in an infinitely long solution, and further disposal mechanisms must be investigated, it does result in a more sustainable use for waste products. Evidently, in certain circumstances, regeneration of adsorption material is a possibility, although there is a large scope for further research in this area. The European Commission have identified waste management as a critical aspect of the circular economy, and recognises the need to involve public authorities, businesses, and investors (European Commission, 2015c). In order to fully engage these entities, it is important to have a viable solution to a difficult-to-solve problem. If the media can be sufficiently exploited to treat water in a sustainable fashion, those entities will have an invested interest in aiming to develop the technologies to their full potential. There is a recognised lack of studies considering industrial symbiosis, logistics and large-scale operation (Mirabella et al., 2014), and it is clear from the review that there is a large scope for development in this area. In this instance, the combination of research and industry, along with public authorities, could work together to fully develop a sustainable method of removing contaminants from water, while avoiding the creation of waste, and therefore leading towards a circular economy.

7 Conclusion

A brief summary of the advantages and disadvantages of each media, along with the raw material availability, is presented in Table 18. Where definite amounts are not available, figures for the parent material have been given. This review indicates that there is a large scope for use of media in water treatment, therefore mitigating current environmental issues such as waste disposal and storage, while aiming to improve water treatment services globally.

242 It is important to note that some media can also be successfully regenerated, once the
243 adsorption potential has been reached, meaning that the filter can be used incurring much less
244 cost than a full replacement. With the use of alternative media, clogging should also be
245 considered. Certain media, although successful adsorbants, may have too fine a particle size,
246 and become clogged within a short period of operation. This can be tested fully at a pilot-
247 scale test.

248 It is, however, important to proceed with caution regarding some of the media, where there is
249 a potential release of toxins or where the pre-treatment costs may not allow for a sustainable
250 approach to be taken. Further recommendations, following this review, are to test the media
251 at larger scale, both individually and also in a multi-layer configuration, where it would be
252 possible to harness the varying adsorptive qualities of different media.

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Figure and Table Captions

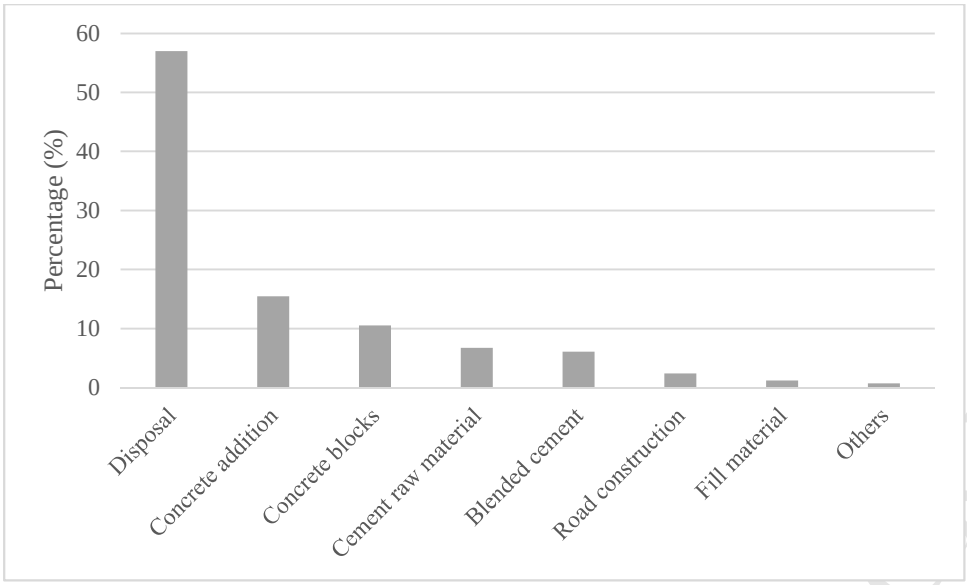

Figure 3

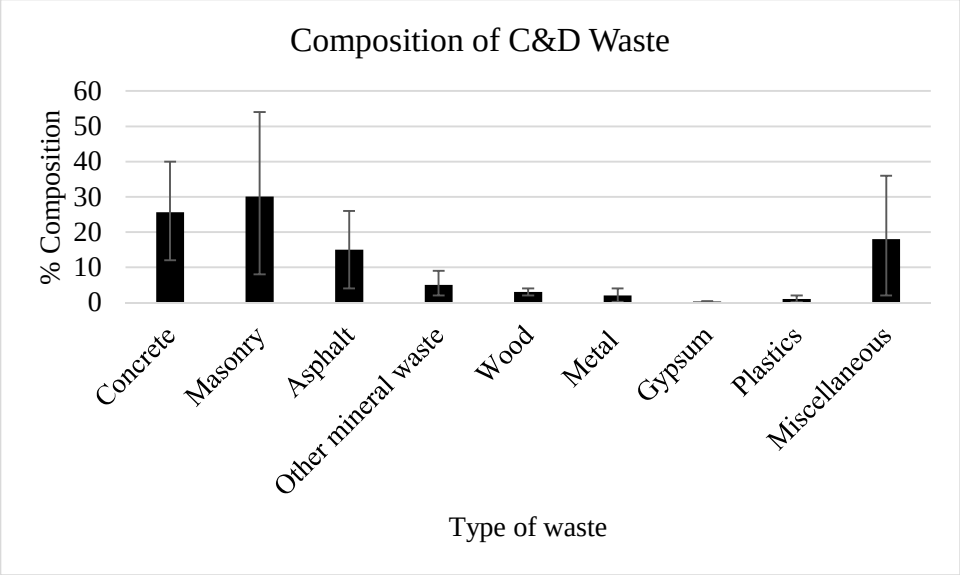

Figure 4

Table 10

	Fly Ash	GGBS	Bayer Residue	Coconut Shell	Coffee Waste	Rice Husk	Crushed Concrete	Masonry Waste
SiO_2	44.5-67%	35%	5-30%					66.52%
Al_2O_3	22.2-30.7%	10%	10-22%					14.2%
Fe_2O_3	1.1-14.4%		20-45%					5.45%
CaO	0.4-4.2%	40%	0-14%					6.06%
BaO	0-0.5%							
MgO	0.3-1.6%	8%						2.35%
Na_2O	0.2-0.9%		2-8%					0.67%
K_2O	0.5-2.9%							2.09%
TiO_2	0.9-1.9%		4-20%					
P_2O_5	0.1-2.7%							
SO_3	0.1-0.5%							0.75%
Carbon %				48.6	57-59	35		
Hydrogen %				6.5	7.1-7.6	4-5		
Oxygen %				44.6	26-23	31-37		
Nitrogen %				0.1	1.2-1.3	0.23-0.32		
Sulphur %				0.1		0.04-0.08		
Ash %						22-29		
Moisture						8-9		
Ca g kg^{-1}							240-551	
Fe g kg^{-1}							17-29	
Al g kg^{-1}							18-30	
P g kg^{-1}							1-13	
Cu mg kg^{-1}							37-87	
Pb mg kg^{-1}							33-87	
Cr mg kg^{-1}							22-115	
Cd mg kg^{-1}							1-20	
Reference	Ward & French (2006)	Ecocem (2015)	EAA (2013)	Daud (2004)	Pujol et al. (2013)	Kumar et al. (2012)	Egemose et al. (2012)	Naceri & Hamina (2009)

Table 11

Contaminant	Adsorption Capacity	Comment/Conditions	Isotherm	Reference
Phosphate	63.2 mg g^{-1}	Raw	Langmuir	Li et al. (2006)
	58.9 mg g^{-1}	Heat activated at 700°C	Langmuir	
	78.4 mg g^{-1}	Acid activated with 0.25 M HCl	Langmuir	
	27.4 g g^{-1}	At 40°C, with initial concentration of 100 mg/L	Langmuir	Ugurlu & Salman (1998)
	20. mg g^{-1}	Raw fly ash	Langmuir	Wu et al. (2006)
	35.3 mg g^{-1}	Salt treated zeolite synthesised from fly ash	Langmuir	
	42. mg g^{-1}	Raw fly ash	Langmuir	Chen et al. (2007)
Humic Acid	126.6 mg g^{-1}	zeolite synthesised from (high calcium) fly ash	Langmuir	Li et al. (2011)
	31.6 mg g^{-1}	zeolite synthesised from (low calcium) fly ash	Langmuir	
	36.6 mg g^{-1}	Raw, single pollutant system	Langmuir	Wang et al. (2008a)
	45.5 mg g^{-1}	Raw, all unburned carbon present	Langmuir	Wang & Zhu (2007)
DOC	0.3 mg g^{-1}	Hydrophobic acid fraction of DOC. Fly ash eluted with methanol	Langmuir	Wei et al. (2011)

Table 12

Contaminant	Adsorption Capacity	Comment/Conditions	Isotherm	Reference
Phosphate	113.9 mg g^{-1}	Raw Heat activated at 700°C	Langmuir	Li et al. (2006)
	345.5 mg g^{-1}	Acid activated with 0.25 M HCl	Langmuir	
	161.6 mg g^{-1}		Langmuir	
	K = 0.47	Acid activated with 2M HCl, experiment @ 30°C	Freundlich	Huang et al. (2008)
	K = 0.62	Acid activated with 2M HCl, experiment @ 40°C	Freundlich	
	K = 0.24	Raw, adsorption experiment @ 30°C	Freundlich	
	K = 0.33	Raw, adsorption experiment @ 40°C	Freundlich	
	75.9 mg g^{-1}	Acid activated with 20% HCl	Langmuir	Pradhan et al. (1998)
	58.1 mg g^{-1}	Neutralised and aggregated, 48 h study	Langmuir	Lopez et al. (1998)
Nitrate	365.8 mg g^{-1}	Acid activated with 20% HCl @ 40°C	Langmuir	Cengeloglu et al. (2006)
	117.8 mg g^{-1}	Original red mud	Langmuir	
Ammonium	18 % removal efficiency	Packed column	N/A	Lopez et al. (1998)

K: Freundlich adsorption capacity factor

Table 13

Contaminant	Adsorption Capacity	Comment/Conditions	Isotherm	Reference
Ammonium	K = 44.9	Activated carbon from coconut shell, at pH 9	Freundlich	Boopathy et al. (2013)
	K = 1875	5:3 Limestone:GAC mix	Freundlich	Hussain et al. (2007)
Nitrate	33.7 mg g^{-1}	NaOH modified coconut shell powder	Langmuir	de Lima et al. (2012)
	10.3 mg g^{-1}	$ZnCl_2$ activated coir pith (from coconut husk)	Langmuir	Namasivayam & Sangeetha (2008)
	18.6 mg g^{-1}	Activated carbon from coconut shell, at pH 2-4	Langmuir	Ohe et al. (2003)
	55.8 mg g^{-1}	Anion exchanger produced from coconut shell	Langmuir	Orlando et al. (2002)
	6.2 mg g^{-1}	Anion exchanger produced from coconut shell	Langmuir	Orlando et al. (2003)
Phosphate	3.0 mg g^{-1}	5:3 Limestone:GAC mix	Langmuir	Hussain et al. (2011)
	200 mg g^{-1}	NaOH modified coconut shell powder	Langmuir	de Lima et al. (2012)
	5.1 mg g^{-1}	$ZnCl_2$ activated coir pith (from coconut husk)	Langmuir	Namasivayam & Sangeetha (2004)
	K = 0.0001 L g^{-1}	Activated carbon from coconut shell	Frumkin	Agrawal et al. (2011)

K: Freundlich adsorption capacity factor

Table 14

Contaminant	Adsorption Capacity	Comment/Conditions	Isotherm	Reference
Nitrate	55.6 mg g^{-1}	Anionic sorbent prepared with rice husk	Langmuir	Katal et al. (2012)
	74.4 mg g^{-1}	Anion exchanger produced from rice husk	Langmuir	Orlando et al. (2002)
	6.2 mg g^{-1}	Anion exchanger produced from rice husk	Langmuir	Orlando et al. (2003)
	70.2 mg g^{-1}	Activated carbon prepared from rice husk	Langmuir	Zhang et al. (2013)
Phosphate	89.6% removal	Chemically activated rice husk	Not specified	Yadav et al. (2015)
	64.3% removal	Raw rice husk	Not specified	
Ammonium	39.8 mg g^{-1}	Biochar prepared from rice husk	Langmuir	Kizito et al. (2015)
	2.6 mg g^{-1}	Rice husk charcoal	Langmuir	Han et al. (2013)
	1.4 mg g^{-1}	Activated carbon prepared from rice husk	Pseudo-second order	Zhu et al. (2012)
Humic acid	45.5 mg g^{-1}	Activated carbon prepared from rice husk	Langmuir	Daifullah et al. (2004)
	8.2 mg g^{-1}	Modified rice husk ash	Langmuir	Imyim & Prapalimrungsi (2010)

Table 15

	Adsorption Capacity	Comment/Conditions	Isotherm	Reference
Phosphate	19.6 mg g^{-1}	Initial P concentration of 1000 mg L^{-1}	Not specified	Egemose et al. (2012)
	17.3 mg g^{-1}	Initial P concentration of 100 mg L^{-1}	Langmuir	Oguz et al. (2003)
	70.9 mg g^{-1}	Initial P concentration of 10 mg L^{-1}	Langmuir	Renman & Renman (2012)
	α:4.976 and β:0.0042	Ordinary Portland cement	Frumkin	Agyei et al. (2002)

Table 16

Contaminant	Adsorption Capacity	Comment/Conditions	Isotherm	Reference
Nitrate	14.1 mg g^{-1}	Brick with particle size <710 µm	Langmuir	Selvaraju & Pushpavanam (2009)
Phosphate	18.2 mg g^{-1}	Brick with particle size <710 µm	Langmuir	Selvaraju & Pushpavanam (2009)
	0.9 mg g^{-1}	La(III) loaded granular ceramic	Langmuir	Chen et al. (2012)
Ammonium	112.4 mg g^{-1}	Novel ceramic adsorbent	Langmuir	Zhao et al. (2013)
	35% removal	Broken brick as biofilter	Not specified	Savage & Tyrrel (2005)

Table 17

Contaminant	Adsorption Capacity	Comment/Conditions	Isotherm	Reference
Ammonium	5.4 mg g^{-1}	Biochar from maple wood, pH adjusted	Langmuir	Wang et al. (2015b)
	54.8 mg g^{-1}	Biochar from mixed wood, 1400 mg L^{-1} initially	Langmuir	Kizito et al. (2015)
	5.3 mg g^{-1}	Untreated biochar from oak sawdust	Langmuir	Wang et al. (2015c)
Nitrate	8.9 mg g^{-1}	Untreated biochar from oak sawdust	Langmuir	Wang et al. (2015c)
	43.5 mg g^{-1}	Activated biochar from pine wood	Langmuir	Chintala et al. (2013)
Phosphate	32 mg g^{-1}	Untreated biochar from oak sawdust	Langmuir	Wang et al. (2015c)

Table 18

Media	Opportunities	Advantages	Disadvantages
Fly ash	17 M t	Nutrient, metal and humic acid removal	Potential for metal leaching
		Disadvantages may be mitigated by pretreatment	
GGBS	<18 M t used in Europe	Limited research available	Solidification in water
			Potential for metal leaching
Bayer residue	>2700 M t	Phosphorus and metal removal	Potential for contaminant leaching
Coconut shell	>60 M t of coconut grown per annum	Metal, dye and anion removal	Expensive carbonization and activation processes required
Tea/Coffee wastes	>5 M t of tea produced per annum	Metal and cation removal	Expensive pre-treatments may be required
		Dye removal when pretreated	
Rice husk	>700 M t	Metal and dye removal	Expensive pre-treatments may be required
Crushed concrete	25% of all C&D waste	Phosphorus and metal removal	Potential for contaminant leaching from concrete constituents
Masonry	30% of all C&D waste	Nutrient, metal and microbiological removal	Variation in raw material
Wood waste	2% of all C&D waste	Nutrient and metal removal	Variation in raw material
			Expensive pre-treatments may be required