INTRODUCTION

Heavy metal is a collective term for the chemical elements that have an atomic density above 4 g/cm³ (Aprile and Bellis, 2020; Abdul-lah, et al., 2019). The heavy metals generated from industrial-based wastewater may contain a large number of elements. These elements can be divided into four major categories: (i) toxic heavy metals (Chromium (Cr), Lead (Pb), Zinc (Zn), Copper (Cu), Nickle (Ni), Cadmium (Cd), and Arsenic (As)) (Altowayti et al., 2020) (ii) strategic metals (Manganese (Mn) or Tungsten (W)) (iii) precious metals (Silver) and (iv) radio nuclides (Uranium (U), Thorium (Th), Americium (Am)) (Wang and Chen, 2009). In terms of environmental threats, categories (i) and (iv) are more preferred for removal from the environment or from point source effluent discharges (Ahalya, 2003). Due to this threat, the Environmental Protection Agency (EPA) and world health organization (WHO) have regulated the maximum acceptable discharge level of concentrations for Zinc (Zn), Copper (Cu), Chromium (Cr), Lead (Pb), Nickel (Ni) and Manganese (Mn) which are 3.0 mg/L, 2.0 mg/L, 0.05 mg/L, 0.1 mg/L, 0.02 mg/L and 0.05-0.5 mg/L, respectively (ATSDR, 2012; EPA, 2016).

The presence of all metal elements cannot be seen with naked eyes in the polluted wastewater. However, it is often the root cause of various severe health issues. Metal toxicity is the term for
the toxic effect of certain metals in certain forms and doses on life. The severity of the toxicity of heavy metals on health is highly variable and depends on varying parameters. They can easily carry the diseases that eventually pose significant hazards to the ecosystem health, especially human and animals. Therefore, extensive removal of toxic heavy metals from the environment has become an important challenge among researchers. Over the years, different approaches have been developed to extract the metal elements from wastewater by prioritizing simple, efficient and cost-effective techniques as a fundamental concept. The suggested methods include chemical precipitation, ion exchange, coagulation and flocculation, adsorption, and membrane processes (Shafiq et al., 2018; Goher, 2015; Ahalya, 2005). However, the drawbacks of these methods include their high cost and lower adsorption capacity in the low concentration range, particularly in the range between 1 to 100 mg/L (Negm et al., 2017; Rahman et al., 2014).

The selection method to be used in the treatment system usually depends on the wastewater characteristics. Each treatment has its own constraints, not only in terms of cost but also in relation to feasibility, efficiency, practicability, reliability, environmental impact, sludge production, operation difficulty, pre-treatment requirements and the formation of chemical residues (Crini and Lichtfouse, 2019; El Nadi and Alla, 2019). For adsorption, the main constraint is the cost of raw materials of activated carbon (AC). According to Research and market (2018) the top producer of AC which is China shows an increasing demand of AC starting from 2011. The market is booming further under the propulsion of national policy and demand growth, and the output of an average annual growth rate (AAGR) is estimated to maintain at least 5.0% during 2018 to 2023. In terms of prices, the cost of coal-based activated carbon increased by more than 20% from RM 3708/ton at the beginning of the year to around RM 4500/ton at the end of the year; the wood-based activated carbon prices increased by about 13.0%. This is mostly due to the increasing demand and higher production costs. In order to solve this problem, many researchers have adjusted the adsorption method by changing the utilization of commercial adsorbent to agricultural waste (Alalwan et al., 2020; Yunus et al., 2019; Saxena et al., 2017; Negm et al., 2017, Demirbas, 2008).

In Malaysia, palm oil is a major agricultural industry which has helped to change the scenario of its agriculture and economy. Nevertheless, despite the obvious benefits, oil palm mills also significantly contribute to the environmental degradation. The Malaysian palm oil mills generate an abundance amount of lignocellulosic biomass derived from fronds, empty fruit bunches and trunks. Annually, about 36 million tons of these wastes are generated and most are either left in the plantations or burned illegally (Azemi et al., 2000). Recently, Oil palm waste has been widely used in AC by applying various activation methods and degrees of processing to have small, low-volume pores that increase the surface area and it is often used as bio-sorbent in the adsorption method. The present study discusses in systematic mode the types of heavy metals originating from wood-based industry, the effects of generated heavy metals towards living things and heavy metals removal by adapting oil palm waste as adsorbent and their future direction.

**Wood-based industrial wastewater**

Several studies show that the main factor to the ecological risk index comes from various anthropogenic influences, such as industrialization and urbanization (Demaku et al., 2020). Wood-based industry encompasses the production of sawn timber, veneer, panel products (including plywood, particleboard, chipboard, and fibreboard), mouldings, and builder joinery and carpentry (BJC), as well as furniture and furniture components (Malaysian Investment Development Authority, 2020). The wood-based panel sectors and furniture manufacturing usually differ in terms of water usage through the production process. Unlike pulp and paper production, the wood-based panel and furniture sectors are commonly considered to be a dry sector with low water consumption. Therefore, their discharge problems are often being neglected. Nevertheless,according to Mamiska (2020) and Bouchareb (2020), wood production plants use between 300 m³ per day and can generate up to ca. 600 MLN m³ of wastewater every year. Results from Chu and Kumar (2020) assessments indicated that pollutant index of these industries on waste water discharge were significantly increased five folds between 2015 and 2017.

The wastewater generated from wood-based industries exerts harmful effects on the
environment due to substantial concentrations of dangerous chemicals. Wide range of various substances are among which wood degradation products, wood extractives, heavy metals or even surfactants introduced during cleaning processes can be found (Kloch and Maminska, 2020). The existence of heavy metals presence in this type of industries is verified in different stages of related production on previous studies (Kloch and Maminska, 2020; Jones et al., 2019). Whereby, arsenic (Ar), copper (Cu), chromium (Cr), zinc (Zn), manganese (Mn) and Iron (Fe) are such metal elements that often associate (Rudi et al., 2020; Demcaka et al., 2019; Jones et al., 2019).

**Heavy metals**

Heavy metal can be categorized as essentials and non-essential toxic; however, they become noxious with long-term exposure or exceeding certain threshold concentrations. In general, heavy metals are non-degradable and some of them were toxic even at trace levels (parts per billion, ppb). The metal ions can bio-accumulate in the main systems of living thing and cause hazardous impacts to plants, animals, and humans (Abdullah et al., 2019).

**Effect of heavy metals toward humans, plants and animals**

With modern life, extensive use of heavy metal in the manufacturing and production industry resulted in metal ions reaching living organisms throughout the disposing wastes. Discharging heavy metals into the river caused the element to gradually accumulate at the bottom of the river. Subsequently, the accumulation of heavy metal will be re-released into the surface water due to environmental changes, such as sediment resuspension and reduction—oxidation reaction that will extensively increase the heavy metal concentrations. Ultimately, heavy metals are absorbed and bio-magnified in food chains, threatening the aquatic life and human health.

According to Sevim (2020), the exposure to heavy metal can lead to human death and disability. The study evinced the potential association between the heavy metal toxicity and cardiovascular disease. Elicit detrimental effects of heavy metals on the Cardiovascular system, resulting in pathophysiological changes, such as increased oxidative stress, inflammatory response, DNA damage, apoptosis, and atherogenic events, including hypertension, coronary and peripheral arteries abnormalities. In addition, heavy metals are often linked with carcinogenic effects. The International agency for Research on Cancer have categorized Arsenic (As), cadmium (Cd), chromium (Cr), and nickel (Ni) compounds as group 1 carcinogens (Kim et al., 2015; Kalagbor et al., 2019). The exposure to these heavy metals is associated with lungs, liver, nose and kidney cancers (Kalagbor et al., 2019).

The aforementioned heavy metals were essentials in some perspective ways (Yunus et al., 2020). However, the toxicity of some essential heavy metals, such as copper (Cu), was also reported. Copper is a beneficial trace element for the growth and development of all known organisms, including humans and other vertebrates. Whereby, Cu acts as a co-factor of metalloenzymes (Pavelkova et al., 2018). Nevertheless, in China, a study by Bao (2020) found that copper gives acute and chronic toxicity effects to their commercially wild freshwater crayfish named Cambaroides dauricus (CD). The long-time exposure to sub-lethal levels of Cu in crustaceans impacted their survival, behaviour, and reproduction, which eventually change the population quantity.

Apart from human and animals, plants were also commonly affected by heavy metal pollution (Abazi et al., 2018). Irrigation is the main sources of heavy metal intake by plants; whereby, 27% of national and international vegetables or plants are being irrigated with wastewater, which includes sewage and industrial effluents (Latif et al., 2020). A pilot study from Hatamian (2020) determines the interaction of lead (Pb) and cadmium (Cd) on growth and leaf morphophysiological characteristics of European hackberry (Celtis australis) seedlings. The results shows that the Pb and Cd (5 mg L\(^{-1}\) for Cd and 15 mg L\(^{-1}\) for Pb) concentration significantly reduced new shoot growth, plant leaf area, SPAD value, leaf water conductance and leaf photosynthesis. Higher reduction was observed in new shoot growth and leaf water conductance over the interaction of 30 mg L\(^{-1}\) Pb levels.

In order to control the risks effects toward living things and environment, many countries have legislated limits for each of heavy metal disposal. In Malaysia Department of Environment is responsible in issuing Environment Quality Act 1974. Under industrial effluent sub-content, using
regulation 2009, standard A prescribed the effluent discharge limit of heavy metal into any inland water within the catchment and standard B to any other inland water or Malaysian waters. Due to the rules and permissible limits, the industrial sector needs to ensure their effluent discharge is below than the allowable limits. Wastewater treatment plant (WWTP) which contains primary, secondary and tertiary treatment stages was developed to control the effluent rate released. This has attracted the attention of researchers to introduce a variety of more effective wastewater treatment methods in proportion to the industrial wastewater sector.

**Method for removing heavy metals**

To date, different processes to eliminate various metal elements from wastewater before entering into the water stream have been developed. The process is such ion exchange, coagulation and flocculation, adsorption, membrane filtration and chemical precipitation. These processes were usually positioned at different stages in WWTP. The descriptions of different process are given in Table 1 along with their advantages and disadvantages (Abdullah et al., 2019).

Researchers employ different efforts and approaches to show the efficacy of the process/method of wastewater treatment they perform. A study conducted by Kloch and Maminska (2020) stated that coagulation using aluminium sulphate (Al₂(SO₄)₃) was among the most popular treatment techniques that are utilized for wastewater treatment from the wood-based industry. The removal efficiency of organic compound is reported up to 50%; however, this technique is accompanied with the introduction of chemicals to the wastewater during treatment that caused secondary pollution and generated toxic sludge, such as Al that needs to be managed.

Meanwhile, membrane separation is widely used as an advanced technology in wastewater treatment due to its lenient operational conditions. However, the high operational costs and low efficiency has restricted the use of this treatment processes, especially in small and medium scales of the industrial sector (Zhu et al., 2019). Out of the mentioned methods, adsorption has been effectively applied in recent decades (Siyal et al., 2020). Continuous research has been conducted since adsorption is considered as a cost-effective and efficient technology as many adsorbents can be provided by forestry and agricultural residues (normally biomass) with one method of “dealing with waste by waste” (Esfahan et al., 2020; Shahrakia et al., 2021).

**Adsorption**

Adsorption in aqueous solution is defined as unit operation that exploits the attraction of solutes (atoms, molecules or ions) in a liquid to a solid surface (Gabelman, 2017). In this process, the solid is called as adsorbent and the solute is known as adsorbate. In order to ensure the treatment process, the bonding interactions between adsorbent and adsorbate should eventuate. The exact nature of the bonding depends on the details on the species of adsorbent and adsorbate involved, but the adsorption process is generally classified as physisorption or chemisorption (Erkey, 2011).

**Table 1. Different methods in removing heavy metals from wastewater (Abdullah et al., 2019)**

| Methods           | Description                                                                 | Advantages                                                                 | Disadvantages                                                                                   |
|-------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| Precipitation     | Metal ions is converted into insoluble precipitates of either hydroxide, sulphide, carbonate and phosphate by using chemical agents. The solid precipitate is later separated by filtration process. | Simple and easy method with high degree of selectivity. Precipitants are commonly inexpensive. | Does not suitable to treat water with high concentration of heavy metals. Requires high amount of precipitate agents. Produces large number of toxic sludge. |
| Coagulation and flocculation | Coagulant with positive charge is present to reduce surface negative charge of particles and allow them to aggregate. The positive charges aggregates will then bind with anionic flocculant. The larger group formed will then be separated using filtration process. | Cost effective if inexpensive coagulant is used. Easy operation. | Deficient metal ions removal. Need to be paired with precipitation method to get the effective removal. Creating unwanted sludge. |
| Adsorption        | Highly porous, large surface area, active functional group of adsorbent materials is used to ensnare the metals elements either using physical or chemical interactions. The adsorbents are later separated from solution by filtration process and undergo regeneration process. | Extensive choices of adsorbents materials. Economical. Easy operation. | Due to Van der Waal’s forces nanosize adsorbents are unable to give encouraging results. Some of the adsorbents need to be modified for maximum adsorption capacity. |
| Ion exchange      | Resin with strong sulfonic acid group (─SO₃H) or carboxylic acid group (─COOH) is mostly utilized in this process. Reversible exchange happened when H+ is released from the functional groups which ultimately allow complexation of metal with the free functional group. | Fast kinetic. Practical process. Uses low-cost materials and resin can be regenerated which resulted as economic method. | Fouling of metal ions on ion exchange media. Fit only in low concentration of metals. High responsive to pH value. Presence of free acids may result in low binding affinity. |
Classification of adsorption

The classification of adsorption is often described as physisorption and chemisorption. This classification depends on the strength of the interaction between the substrate and adsorbate. This interaction is determined during the isotherm and kinetic study. As for example, if the kinetic model is fitted to a pseudo second-order model, it assumes that two surface sites can be occupied by one adsorbate ion; these suggested that the adsorption is classified as chemisorption. (Abesekara et al., 2020)

Physisorption is a broad term that describes all weak electrostatic interactions including Van Der Walls, hydrogen bonding and the dipole dipole interactions between the sorbent and sorbate whereby the interactions are typically range from 0.2 to 4 kJ/mol (Sims et al., 2019). These bonds are considered the weakest of interactions and can be easily broken. Physisorption takes place at the low temperature and decreases with increasing temperature, as shown in Figure 1 (Milan, 2014; Mathew et al., 2016).

Chemisorption proceeds by exchange or sharing of electrons between the sorbate and sorbent to create a covalent or iconic bond (Kwon et al., 2011). In other words, chemisorption is based on chemical reactions between the adsorbate and the surface sites of the adsorbent (Patel, 2019). The strong chemical bond provided from adsorbate and adsorbent make it more difficult to reverse and requires more energy to remove the adsorbed molecules than physical adsorption does (Sarbu and Sebarchievici, 2017). Chemisorption first increases along with the temperature and there is an optimal strength of chemisorption (called “the volcano curve theory”) as shown in Figure 2 (Milan, 2014; Mathew et al., 2016). The differences between physisorption and chemisorption are summarized in Table 2 (Milan, 2014).

In general, chemisorption is more popular in heavy metal removal, because it has stronger interactions and higher adsorption capacity towards heavy metals (Khulbe and Matsuura, 2018).

Adsorption process

The adsorption process can be thought of as the separation of the adsorbent between the fluid phase and the adsorbent. If the solid and fluid are placed in contact for long time, an equilibrium distribution is reached and this equilibrium can be described quantitatively. The equilibrium behaviour is characterized by expressing the amount of adsorbate adsorbed as a function of partial concentration at a fixed temperature. Such equilibrium model was called isotherm (Gableman, 2017). The analysis of the isotherm data is important to develop an equation that accurately represents the results and which could be used for design purposes (Elsayed et al., 2020). The Langmuir and Freundlich isotherms

![Figure 1. Adsorption isobar for physisorption](image1)

![Figure 2. Adsorption isobar for chemisorption](image2)

| Table 2. Comparison between physisorption and chemisorption |
|-------------------------------------------------------------|
| Properties | Physisorption | Chemisorption |
| Type of bonding forces | Van Der Wals | Similar to chemical bond |
| Adsorption heat | Low | High |
| Chemical change of adsorptive | None | Formation of a surface compound |
| Reversibility | Reversible | Irreversible |
| Activation energy | Very low | High |
| Formation of multi-layer | Yes | No |
were two common isotherms used in the adsorption’s studies (Table 3). The Freundlich isotherm is usually applied to characterize heterogeneous (multilayer) adsorption on the adsorbent surface, whereas the Langmuir isotherm was used to describe homogenous (monolayer) adsorption on the adsorbent surface (Duraisamy et al., 2020).

**Factor Affecting Adsorptions**

The interaction between adsorbate and adsorbent is influenced by some parameters, namely the operating parameters pH of solution, mass of adsorbent, and contact time (Othman et al., 2012). In order to evaluate the exact responses of these parameters under experimental conditions, batch sorption modelling is deemed pivotal.

**Effect of contact time**

Contact time is one of the major parameters that govern the adsorption processes. Determination of the optimum contact time for adsorption aims to determine the time needed by the adsorbent to absorb the maximum number of heavy metals. A study by Elsayed (2020) indicated that the removal percent of pollutants increases along with the contact time. According to Duraisamy (2020), this may due to the availability of greater biosorbent surface area at the opening of the adsorption of corresponding metal ions in the medium. Table 4 shows the summarization of previous study on the influence of contact time on adsorption of heavy metal removal.

**Effect of pH**

The pH is the most susceptible parameter in the adsorption studies due to the fact that H⁺ is a strongly competing adsorbent. The pH affects the specification of metal ions and the ionization of surface functional groups (Elsayed et al., 2020). In addition, pH is considered to play a vital role inside the adsorption system, especially in the aqueous solution, since it affects the character of each ion to be removed and the adsorbents (where

**Table 3.** Recent view on best fitted isotherm and kinetic model on heavy metal removal

| Adsorption isotherm | Kinetic model | Sources |
|---------------------|---------------|---------|
| Langmuir            | Freundlich    |         |
|                     | Pseudo first order model | Singh et al., 2020 |
|                     | Pseudo second order model | Sayed et al., 2020 |
|                     | x             | x       |

**Table 4.** Efficient contact time on adsorption of heavy metals

| Adsorbent            | Heavy metals        | Remarks | Source               |
|----------------------|---------------------|---------|----------------------|
| Palm Kernel Shell    | Chromium, Lead, Zinc and Cadmium | Highest contact time at 120 min | Baby and Hussein, 2020 |
| Palm Kernel Shell    | Cadmium             | Highest contact time at 150 min, decreases at 180 min | Faisal et al., 2019 |
| Pomegranate peel     | Nickle              | Sharply increased during the first 30 min; gradually achieved the equilibrium in 150 min | ElSayed et al., 2020 |
| Kenaf Fibre          | Iron, Manganese, Zinc, Arsenic, Copper, Nickle | The contact time will eventually reach a maximum value at a certain point and remain constant | Saeed et al., 2020 |
| Mango Leaf           | Chromium and Iron   | Adsorption takes place at 120 min. of interaction time | Duraisamy et al., 2020 |
| Coffee Shell         | Lead                | In the first 30 min. until min. 90 the adsorption rate is slow; however, from minute 90 until min. 150 ultimately the adsorption equilibrium occurs. | Juniar et al., 2019 |
| Chestnut Shell       | Chromium            | An increase in adsorption was seen at initial 60-300 min thereafter remained constant | Singh et al., 2020 |
| Jackfruit Peel       | Lead and Cadmium    | Range of between 15 minutes to 24 hours. Adsorption was rapid during the first 1 hour of contact but gradually decreases up to the point where equilibrium is achieved. | Ibrahim et al., 2020 |
| Oil Palm Ash         | Manganese           | Within 80 min the system reached equilibrium | Chowdhury et al., 2011 |
the adsorption phenomena disappear and change to precipitation when the pHs is set to more than 7) (Saeed et al., 2020). Thus, in order to achieve the maximum adsorption capacity during the batch study, a well-defined pH range is usually identified. Numerous previous studies observed that the adsorption of metal ions was significantly increased as the pH shifted from low to high (Table 5).

**Effect of adsorbent dose**

The effect of the adsorbent mass usually determined the capacity of a solid adsorbent for a certain concentration of adsorbate in a solution. The availability of the exchange sites or surface area may contribute on the effect of adsorbent dose toward the adsorption capacity (Elsayed et al., 2020; Mahmudi et al., 2020). Table 6 shows the effect of adsorbent dose on removal capacity of heavy metals from previous study.

**Activated Carbon**

Large numbers of studies have been dedicated to find suitable and cheap adsorbents for the treatment or removal of heavy metal from wastewater. The concept of L-3 class (i.e. low cost, locally available, low technologically prepared and used) of adsorbents are the solutions that are being studied by many researchers worldwide (Baneerjee, 2020). The adsorbents investigated on heavy metal treatment in previous research include cellulose nanofibers, zeolites, carbon nanotubes, agro-industrial waste materials, granular or powdered activated carbon (AC), and modified AC (Shahrakia et al., 2021). Among which activated carbon (AC) is a popular adsorbent due to its high adsorption capacity owing to its porous structure and surface chemical groups. In addition, AC was also named as versatile adsorbent, since its performance characteristics can be tailored by varying the precursor, heating temperature and activation method (Gabelman, 2017).

In general, the surface areas of AC can be up to 3000 m²g⁻¹, whilst the surface area of commercially available AC is approximately 1000 m²g⁻¹ as shown in Table 7. This high surface area results from the development of mainly microporous and mesoporous of different size and shape. Different pore size distribution influences the performance properties of the AC. Sudaryanto (2006) found that macro-pores have little contribution to the development of surface area. The AC pores are categorized by volume in accordance with the International Union of Pure and

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**Table 5. Effect of pH value adjustment towards the adsorption capacity of heavy metals**

| Adsorbent           | Heavy metals          | pH range | Optimum pH value | Adsorption capacity | Source                  |
|---------------------|-----------------------|----------|------------------|---------------------|-------------------------|
| Pomegranate peel    | Nickle                | 4 to 9   | 9                | 98%                 | Elsayed et al., 2020    |
| Kenaf Fibre         | Iron, Manganese, Zinc, Arsenic, Copper, Nickle | 3 to 11  | 7                | Between 5% to 30%   | Saeed et al., 2020      |
| Mango Leaf          | Chromium and Iron     | 2 to 10  | 8                | 99% and 99.5%       | Duraismay et al., 2020  |
| Palm Kernel Shell   | Chromium, Lead, Zinc and Cadmium | 2 to 6   | 6                | 60% to 80%          | Baby and Hussein, 2020  |
| Chestnut Shell      | Chromium              | 2 to 12  | 7                | 78%                 | Singh et al., 2020      |
| Banana Peel         | Copper, Nickle and Lead | 0.6 to 7.4 | 5.7 to 7.4 | 40%, 51% and 54%    | Thuan et al., 2017      |
| Jackfruit Peel      | Lead and Cadmium      | 4 to 9   | 7                | 50% to 90%          | Ibrahim et al., 2020    |
| Pistachio Hull      | Nickle                | 2 to 10  | 6                | 60% to 90%          | Beidokhti et al., 2019  |
| Oil Palm Ash        | Copper                | 2 to 8   | 8                | 50% to 94%          | Chowdhury et al., 2011  |
| Oil palm Shells     | Nickel, Lead and Chromium | 3 to 10 | 8                | Up to 70%           | Rahman et al., 2014     |

**Table 6. The effect of adsorbent dose on removal capacity of heavy metals from previous study**

| Adsorbent           | Adsorbent Dose | Heavy metals          | Removal capacity     | Source                  |
|---------------------|----------------|-----------------------|----------------------|-------------------------|
| Mango Leaf          | 20 to 100 mg/L | Chromium and Iron     | Chromium: from 93.4% to 99.6% | Duraismay et al., 2020 |
| Chestnut Peels      | 0.2 to 1.0 g   | Chromium              | 60% to 79%           | Singh et al., 2020      |
| Banana Peels        | 0.9 to 2.4 g/L | Copper, Nickle and Lead | Copper: 40%, Nickle: 51% and Lead: 54% | Thuan et al., 2017      |
| Pistachio Hull      | 5 to 30 g/L    | Nickle                | 66% to 76%           | Beidokhti et al., 2019  |
Applied Chemistry (IUPAC 1972) classification system. Table 8 lists the classification of pores by their diameter.

Numerous kinds of carbonaceous materials can be utilized as AC; however, as shown in Table 8 coconut shell (CS) and coal are commonly used in industrial manufacturing to make commercial AC. Despite their ideal adsorption efficiency, high demand has required high investment costs in large-scale applications and led to escalation of their prices. Therefore, attention has been drawn to finding affordable and unconventional precursors, such as agricultural wastes.

Agricultural wastes have been broadly utilized as biosorbents since they are inexpensive and abundantly available in large volumes as the residues from agricultural activities (Rudi et al., 2020; Pyrzynska, 2019). The sorption capacity of different biosorbents of plant origin whose efficiencies for the uptake of heavy metal have been reported previously include honeydew peels (Yunus et al., 2019), grape (Melia et al., 2018), wheat (Melia et al., 2018), barley (Rajczykowski et al., 2018; Melia et al., 2018), coffee pulp (Aguilar et al., 2019), rice waste (Ravi et al., 2017; Garcia, 2018; El Nadi, and Alla, 2019; Obayomi, 2019; Table 9.

### Table 7. Surface area of commercial AC

| Properties/Supplier | Commercially available activated carbon |
|---------------------|-----------------------------------------|
|                     | HANYAN | HANYAN | Zhulin Carbon | Concopt Ecotech | Innova Corporate |
| Starting materials  | Coconut shell | Coal | Coal | Coconut Shell | Coconut Shell |
| Surface area (m²/gm) | 950-1500 | 500-950 | 900-1100 | 900-1350 | 400-1200 |

### Table 8. Classification of pores by diameter

| Types of pore | Diameter of pore | Characteristic of pore |
|---------------|------------------|------------------------|
| Micropore     | D<20Å            | Superimposed wall potential |
| Mesopore      | 20Å<D<50Å        | Capillary condensation  |
| Macropore     | D>50Å            | Effectively Flat walled |

### Table 9. Adsorption capacity of biosorbents obtained from agricultural wastes on the removal of different metal elements

| Adsorbents       | Metal elements | Qₑ (mg/g) or removal percentage (%) | Sources                        |
|------------------|----------------|------------------------------------|--------------------------------|
| Coffee Pulp      | Chromium (Cr)  | 13.48 mg/g                         | Aguilar et al., 2019          |
| White yam        | Cadmium (Cd)   | 22.4 mg/g                          | Asuquo et al., 2018           |
| Brassica Campestris waste stem | Nickel (Ni) | 1.1 mg/g                           | Shaikh et al., 2018           |
|                  | Chromium (Cr)  | 95 mg/g                            |                                |
| Canola seeds     | Lead (Pb)      | 44.25 mg/g                         | Affonso et al., 2019          |
|                  | Cadmium (Cd)   | 52.36 mg/g                         |                                |
| Rice husk        | Zinc (Zn)      | 94.33 %                            | El Nadi and Abd Alla, 2019    |
|                  | Chromium (Cr)  | 89.20 %                            |                                |
| Banana peel      | Copper (Cu)    | 14.3 mg/g                          | Thuan et al., 2017            |
|                  | Nickel (Ni)    | 27.4 mg/g                          |                                |
|                  | Lead (Pb)      | 34.5 mg/g                          |                                |
| Rice straw       | Chromium (Cr)  | 97.12%                             | Kumar et al, 2017             |
| Jackfruit peels  | Lead (Pb)      | 10.1 mg/g                          | Ibrahim et al., 2020          |
|                  | Copper (Cu)    | 17.5 mg/g                          |                                |
|                  | Cadmium (Cd)   | 20.0 mg/g                          |                                |
|                  | Manganese (Mn) | 76.9 mg/g                          |                                |
|                  | Iron (Fe)      | 4.40 mg/g                          |                                |
| Pistachio Hull Waste | Nickel (Ni) | 14 mg/g                            | Beidokhti et al., 2019        |
| Ground Nut shell | Cadmium (Cd)   | 70.64%                             |                                |
| Pongamia Pinnata | Cadmium (Cd)   | 79.9%                              | Vinaykumar et al., 2019       |
| Onion skin       | Lead (Pb)      | 10.75 mg/g                         |                                |
Bożęcka et al., 2020), ground nutshell (Obayomi, 2019; Garcia, 2018), white yam (Asuquo et al., 2018) and soya beans (Obayomi, 2019; Garcia, 2018). Table 9 shows the utilization of agricultural waste and their adsorption capacity on the removal of varied heavy metals.

**Oil palm agriculture waste**

In Malaysia, the main agricultural commodities grown are such oil palm, rubber, rice, cocoa and coconut. According to Malaysian Oil Palm Board (MPOB), Malaysia produced bisection of the world palm oil production and the production has increased up to 5.90 million hectares in 2019, approximately 0.9% in comparison to 5.85 million hectares in 2018. Among these numbers, Johor has the largest oil palm plantation area compared to other states in peninsular Malaysia, as tabulated in Table 10 (MPOB, 2019).

Malaysia, as the world’s leading dealer in the palm oil industry, faces a difficult challenge in handling the palm oil waste. According to Lee (2017), for every 1 kg of crude palm oil produced, approximately 4 kg of waste are generated. Peninsular Malaysia recorded 77% of oil palm agriculture residue approximately 17 Mt as shown in Figure 3 (Hamzah et al., 2019). Palm kernel shell (PKS), fronds (OPF), trunk (OPT), leaves (OPL), mesocarp fibre, and empty fruit bunch (EFB) were among the aforementioned residues. The EFB, mesocarp fiber and PKS are collected during the pressing of sterilized fruits whilst OPF and OPL are available daily throughout the year when the palms are pruned during the harvesting of fresh fruit bunch for the production of oil. OPT is obtained during the replantation of the oil palm trees that occurred every 15-20 years (Marsin et al., 2018). Recently, abundant of research output proved that each part of oil palm waste could be converted into varieties of value-added products.

**Oil palm waste as adsorbents**

Globally, various technologies have been applied to convert the palm oil waste to bio-based products such as pellet for feedstock, fertilizers, fillers, bioplastics and adsorbent. In preparation as adsorbent, oil palm waste is usually treated under specific conditions. The activation can be done via physical or chemical activation, following the simplified structure presented in Figure 4. For physical activation, two steps were involved. The first step is pyrolysis, where oil palm

| State          | Mature | Immature | Total  | %  |
|----------------|--------|----------|--------|----|
| Johor          | 694,097| 64,439   | 758,535| 12.9|
| Kedah          | 81,794 | 8,927    | 90,721 | 1.5 |
| Kelantan       | 127,221| 44,124   | 171,345| 2.9 |
| Melaka         | A 52,083| 5,257 | 57,340 | 1.0 |
| Negeri Sembilan| 170,970| 18,009  | 188,979| 3.2 |
| Pahang         | 668,236| 100,161  | 768,397| 13.0|
| Perak          | 363,813| 43,790   | 407,603| 6.9 |
| Perlis         | 842    | 49       | 891    | 0.0 |
| Pulau Pinang   | 13,445 | 355      | 13,800 | 0.2 |
| Selangor       | 117,558| 13,112   | 130,671| 2.2 |
| Terengganu     | 153,656| 27,065   | 180,721| 3.1 |
| Sabah          | 1,353,812| 190,669 | 1,544,481| 26.18|
| Sarawak        | 1,419,295| 167,378 | 1,586,673| 26.9|
| Total          | 5,216,822| 683,335 | 5,900,157| 100.0|

Table 10. Oil palm planted area as December 2019 (MPOB, 2019)
waste is carbonized and then followed with the carbon activation using steam or oxidation gases. Meanwhile, for the activation of carbon through chemical activation, the oil palm waste is saturated with activation chemical. The saturated chemical and raw materials are then simultaneously heated under various temperatures. After designated time, the raw materials are brought out and washed with distilled or hot tapped water (depends on the suggested method) to remove chemicals, and activated carbon is obtained. In general, chemical activation is preferred among researchers as it saves time and less activated carbon is burned (Yeow et al., 2021). Table 11 shows the process of activated carbon production steps from numerous sources of the previous research.

In terms of surface characterization, Scanning Electron Microscope (SEM) is commonly utilized as platform media in a way to identify the changes for pre- and post- development of pore structure. A study from Abu Sari (2014) made comparison on the morphology structure between oil palm empty fruit bunch (EFB) and rice husk biochars. The results show significant differences on both wastes (Figure 5 (a) and (b)). In comparison, the pores on rice husk biochar are not well shaped with diminished structure of pores. Small pores also were detected on the rough surface of rice husk biochar, while EFB provides more competent pore structures. Tobi (2019) also presented similar results of EFB, where EFB along with oil palm fronds developed pore networks of divine honeycomb pattern, compared to uneven pore development from palm kernel shell (Figure 6). This well-developed porous network is an indication of high surface area on which metal ions can be deposited.

Oil palm is made up from lignocellulosic material which is rich in carbohydrates in the form of starch and sugar and containing different compositions which making them excellent precursors for adsorbent (Ahmad et al., 2011). One of the most vital components of plant cell walls is β-D-glucopyranose units which has been identified in lignocellulosic materials. Each β-D-glucopyranose unit contains one primary hydroxyl group and two secondary hydroxyl groups that are commonly involved in chemical reactions (Vakili et al., 2014). The adsorbents obtained from various parts of oil palm biomass show different morphologies proportional to their composition, as shown in Figure 7 a, b and c, as they are transformed into adsorbents for the purpose of adsorption process.

In terms of the heavy metal removal, the contribution of electron pairs on the functional groups of the lignocellulosic will bind to form the heavy metal form complexes with metal ions in solution (Vakili et al., 2014). A study from Lim (2016) found that the chemically modified cellulose could potentially achieve efficient adsorption capacity of heavy metal ions, whereby, it can adsorb metal ions via ion exchange which contributed from the active sites present on them. Several other studies also have proven the potential of
different parts of oil palm waste as heavy metal removal in aqueous solution by using different types of modifications agents, as shown in Figure 8 (Barros et al., 2020; Baby and Hussein, 2020; Lim et al., 2016; Faisal et al., 2019).

Results have shown that chemically modifying waste improves the heavy metal removal and sorption capacity. The removal percentage was up to 99% (Figure 9). This waste can be modified by treating it with different chemical agents (e.g., alalis, acids, organic compounds, etc.). Such chemical modification increases the level of metal uptake by releasing certain soluble organic compounds within the biomass (Vakili et al., 2014).

As in solid state, a study from Rasli (2017) shows their X-Ray diffraction (XRD) results indicating that the most prominent peak in the oil palm fronds is observed at 22.6°, which demonstrates the crystalline structure of the cellulose. Crystalline solids have well-defined edges and faces, diffract x-rays, and tend to have sharp melting points. The results also show (Figure 9) the crystalline index (CI) of 24.31% for the raw oil palm fronds, which progressively increased after alkali treatment (52.46%) and bleaching treatment (68.75%). The increment of this index was due to the progressive removal of the hemicelluloses and lignin.

On the other hand, as mentioned in factor affecting adsorption such factors (pH value, contact time, and AC dose) also implicate the adsorption capacities of oil palm waste AC. Therefore, in order to evaluate the oil palm waste AC responses toward these factors, Table 12 summarized the respective findings.

In the acquisition of high adsorption capacity, the optimum values of the factor influencing

Figure 6. Micrograph image of EFB, palm oil fronds and kernel shells (1000X, 500X and 1000X) (Tobi et al., 2019)
adsorptions were roughly in the same range without any significant differences, as seen in Table 12. In general, the relevance of metal ions toward the surface of the adsorbent is highly affected by the pH of the solution. Low values of the adsorption capacity were noticed in the strong acidic medium.
(pH<7) due to the H⁺ ions exchange hindrance, while the higher values of the adsorption capacity obtained in the weak acidic and neutral medium due to a greater ratio of positive metal ions (Baby and Hussein, 2020; Al Othman et al., 2020). The data shows that the optimum pH value range is between 4 and 8. However, according to Baby and Hussein (2019) under basic conditions, formation precipitation of metal ions as their respective hydroxide can influence the adsorption results; therefore, selection of maximum adsorption under acidic environment below pH < 7 should also be considered.

In terms of contact time, the total value varies from 60 minutes to 120 minutes, before it approaches a static value after which no further change in uptake has been observed. The adsorption rate was found to increase as the adsorbent dosage escalated. By which the maximum number of active sites may be responsible for the removal of more ions at their surfaces (Baby and Hussein, 2020). In a period of time, the surface of adsorption sites was fully occupied; these reflected the equilibrium point of the system. The

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**Table 12. Optimum values of affecting factors for heavy metals adsorption using Oil Palm AC**

| Oil Palm AC       | Heavy Metals | Factor affecting adsorptions (Optimum values) | Source                        |
|-------------------|--------------|-----------------------------------------------|-------------------------------|
|                   |              | pH value | Contact time | AC dose |                              |
| Palm Kernel Shell | Lead         | 4        | 60 min      | 1.5g    | Baby and Hussein, 2019       |
|                   | Chromium     | 6        | 60 min      | 1.5g    |                              |
|                   | Cadmium      | 6        | 90 min      | 2.0g    |                              |
|                   | Zinc         | 6        | 120 min     | 2.0g    |                              |
| Oil Palm Leaves   | Manganese    | 7        | 60 min      | N/A     | Alothman et al., 2019       |
|                   | Lead         | 6        | 60 min      | N/A     |                              |
|                   | Cobalt       | 7        | 60 min      | N/A     | Chowdhury et al., 2011      |
| Oil Palm Ash      | Manganese    | 7        | 80 min      | N/A     | Chowdhury et al., 2011      |
| Palm Kernel Shell | Chromium     | 6        | 120 min     | 0.25g   | Baby and Hussein, 2019       |
|                   | Lead         |           |            |         |                                |
|                   | Zinc         |           |            |         |                                |
|                   | Cadmium      |           |            |         |                                |
| Palm Fruit Fibre  | Lead         | 5        | 120 min     | N/A     | Ooiia and Ong, 2019          |
remaining vacant sites were difficult to be captured by metal ions due to the repulsive forces between the adsorbate, i.e. the metal present in solid and bulk phases. The adsorbent dose is crucial if research is conducted to adapt into the industrial WWTP system. The determination of AC dose will indicate the minimum possible dosage for the maximum adsorption of metal ions and gives initial theory of system design and costs. In general, Baby and Hussein (2019) suggested that adsorption is almost directly proportional to the amount of the adsorbent dosage.

CONCLUSIONS

Considering that heavy metals are poisonous elements, releasing them into the environment as a result of industrial activity is a serious threat to human life and other living organisms. The current adsorption methods of heavy metal wastewater treatment are expensive due to the soaring demand of commercial activated carbon and also inefficient at low concentrations of metal ions. Converting agricultural waste into value-added adsorbents is a way to solve the disposal issue and substituting the conventional adsorbents. The utilisation of agricultural waste from oil palm as an adsorbent in Malaysia has gained recognition owing to its abundance, relatively low cost and rich in lignin, cellulose and hemicellulose. The physical and chemical modifications on oil palm waste are able to transform them into value added adsorbents with high adsorption capacity reaching up to 99% metals removal. The design of a suitable system that consumes the lowest amount of adsorbate that affects the cost is important as to be utilized in a real WWTP industrial system. Thus, the oil palm waste should be explored further in terms of factor affecting adsorption which ultimately will influence the adsorption rate, surface area and porosity.

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REFERENCES

1. Abazi, A.S., Sallaku, F., Bytyqi, P., Hyseni Spahi, M., Millaku, F. 2018. Heavy Metal Concentrations along the Banks of the Sitnica River and in Four Types of Herbaceous Plants. Journal of Ecological Engineering, 19(5), 1-9.
2. Abesekara, M.N., Kosvinna, K.N.R and Amarasinghe, B.M.W.P.K. 2020. Adsorption and desorption studies of Ni²⁺ ions on to coconut shell char. IOP Conf. Ser.: Earth Environ. Sci., 427, 012005.
3. Abdullah, N., Yusofa, N., Lau, W.J., Jaafar, J., and A.F. Ismail 2019. Recent trends of heavy metal removal from water/wastewater by membrane. Journal of Industrial and Engineering Chemistry, 76(25), 17-38.
4. Abu Sari, N., Ishak, F., and Bakar, R. 2014. Characterization of oil palm empty fruit bunch and rice husk biochars and their potential to adsorb arsenic and cadmium. American Journal of Agricultural and Biological Science, 9, 450-456.
5. Agency for Toxic Substances and Disease Registry (ASTDR) 2020. Toxicological Profile Division of Toxicology and Human Health Sciences.
6. Aguilar, D.L.G., Miranda J.P.R., Muñoz J.A.E and Fredy J. 2019. Betancur PCoffee Pulp: A Sustainable Alternative Removal of Cr (VI) in Wastewaters Processes, 7, 403.
7. Ahalya, N., Kanamadi R.D., and Ramachandra T.V. 2005. Biosorption of chromium (VI) from aqueous solutions by the husk of Bengal gram (Cicer arietinum). Electronic Journal of Biotechnology, 8(3).
8. Ahalya, N., Ramachandra, T.V. and Kanamadi R.D. 2003. Biosorption of Heavy Metals. Res J.Chem Environ, 7(4), 71-79.
9. Ahmad, T., Rafatullah, M., and Ghazali, A. 2011. Oil palm biomass–based adsorbents for the removal of water pollutants – A review. Journal of Environmental Science and Health, Part C, 29, 177–222.
10. Al Othman, Z.A., Habila, M.A., Moshab, M.S., Al-Qahtani, K.M., AlMasoud, N. and Al-Senani G.M., 2020. Fabrication of renewable palm-pruning leaves based nano-composite for remediation of heavy metals pollution. Arab J Chem; 13(4), 4936-44.
11. Alalwan H.A., Kadhom M.A., Alminshid A.H. 2020. Removal of heavy metals from wastewater using agricultural byproducts. Journal of Water Supply: Research and Technology-Aqua, 69(2), 99–112.
12. Altowayti, W.A.H, Almoalemi, H., Shahir, S., Othman, N. 2020. Comparison of culture-independent and dependent approaches for identification of native arsenic-resistant bacteria and their potential use for arsenic bioremediation, Ecotoxicology and Environmental Safety, 205, 111267.
13. Aprile, A. and Bellis L.D. 2019. Editorial for Special
Issue Heavy Metals Accumulation, Toxicity, and Detoxification in Plants. Int. J. Mol. Sci, 21, 4103.

14. Asuquo, E.D., Martin, A.D. and Nzerem, P. 2018. Evaluation of Cd(II) Ion Removal from Aqueous Solution by a Low-Cost Adsorbent Prepared from White Yam (Dioscorea rotundata) Waste Using Batch Sorption Chem Engineering, 2, 35.

15. Baby, R., Hussein M.Z. 2019. Application of palm kernel shell as bio adsorbent for the treatment of heavy metal contaminated water. Journal of Advanced Research in Applied Mechanics, 60(1), 10-16.

16. Baby, R. and Hussein M.Z. 2020. Ecofriendly Approach for Treatment of Heavy-Metal-Contaminated Water Using Activated Carbon of Kernel Shell of Oil Palm Materials, 13, 2627.

17. Banerjee, K. 2020. Biosorbents as Green Solution to Remove Heavy Metals from Waste Water - Review. J. Adv. Sci. Eng., 6(S2), 43-45.

18. Barros, A.H., Tejada-Tovar, C., Villabona-Ortíz, A., Gonzalez-Delgado, A.D. and Benitez-Monroy J. 2020. Cd(II) and Ni(II) uptake by novel biosorbent prepared from oil palm residual biomass and Al2O3 nanoparticles. Sustainable Chemistry and Pharmacy, 15, 100216.

19. Beidokhti, M.Z., Taghi (Omid) Naeni S., and Gahroudi M.S.A. 2019. Biosorption of Nickel (II) from aqueous solutions onto pistachio hull waste as a low-cost biosorbent. Civil Engineering Journal, 5(2).

20. Bouchareb, R., Derbal, K., Özay, Y., Bilici, Z. and Demirbas, A. 2008. Heavy metal adsorption onto agro-based waste materials: a review. J Hazard Mater., 15, 157(2-3), 220-9. PMID: 18291580.

21. Bouchareb, R., Derbal, K., Özay, Y., Bilici, Z. and Demirbas, A. 2008. Heavy metal adsorption onto agro-based waste materials: a review. J Hazard Mater., 15, 157(2-3), 220-9. PMID: 18291580.

22. Chen, J. and Kumar, A. 2020. Assessment of wood industrial pollutants based on emission coefficients in China. Holzforschung, 74, 11, 1071–1078, DOI: https://doi.org/10.1515/hf-2019-0201.

23. Crini, G. and Lichtfouse, E. 2019. Advantages and disadvantages of techniques used for wastewater treatment. Environmental Chemistry Letters, Springer Verlag, 17(1), 145-155.

24. Demaku, S., Jusufi, K. and Kastrati, G. 2020. Contamination of Environment with the Heavy Metals Emitted from a Cement Factory, Kosovo. Journal of Ecological Engineering, 21(8), 75-83.

25. Demcaka, S., Balintovaa M., Demcakovab M., Csaichb K., Zinicovscaia I., Yushind N and Fountasyeva M. 2019. Effect of alkaline treatment of wooden sawdust for the removal heavy metals from aquatic environments Desalination and Water Treatment 155, 207–215.

26. Dizge, N. 2020. Combined natural/chemical coagulation and membrane filtration for wood processing wastewater treatment. Journal of Water Process Engineering, 37, 101521.

27. Duraisamy, R., Mechoro, M., Seda, T. and Khan, M.A. 2020. Potential of Mangiferaindica activated carbon for removal of chromium and iron, Cogent Engineering, 7:1, 1813237. Ecotoxicology and Environmental Safety, 205, 111267.

28. El Nadi and Abd Alla 2019. Removing Heavy Metals from Wastewater by using Rice Husk Wastes Fiber. International Journal of Engineering and Advanced Technology, 8, 6.

29. Elsayed, A., Osman, D., Attia, S., Ahmed, H., Shoukry, E., Mostafa, Y., Taman, A. 2020. A Study on the Removal Characteristics of Organic and Inorganic Pollutants from Wastewater by Low Cost Biosorbent. Egyptian Journal of Chemistry, 63(4), 1429-1442.

30. Erkey, C. 2011. Thermodynamics and Dynamics of Adsorption of Metal Complexes on Surfaces from Supercritical Solutions.

31. Esfahlan, A.J., Esfahlan, R.J., Tabibiazar, M., Roufegarinejad, L. and Amarowicz, R. 2020. Recent advances in the use of walnut (Juglans regia L.) shell as a valuable plant-based bio-sorbent for the removal of hazardous materials RSC Adv, 10, 7026-7047 DOI: 10.1039/C9RA10084A.

32. Faisal, M., Gani, A., and Muslim, A. (2019) Cadmium Adsorption onto Naoh Activated Palm Kernel Shell Charcoal International Journal of GEOMATE, 17(64), 252-260.

33. Gableman, A. 2019. Adsorption: Back to basic: Part 1, 48-53.

34. Garcia, P.G. 2018. Activated carbon from lignocellulose precursors: A review of the synthesis methods, characterization techniques and application. Renewable and Sustainable Energy Reviews, 82, 1393-1414.

35. Goher, M.E., Hassan, A.M., Abdel-Moniem, I.A., et al. 2015. Removal of aluminum, iron and manganese ions from industrial wastes using granular activated carbon and Amberlite IR-120H. Egypt J. Aquat. Res., 41, 155–164.

36. Hatamian, M., Rezaei Nejad, A., Kafi, M. et al. 2020. Interaction of lead and cadmium on growth and toxicification in Plants. Int. J. Mol. Sci, 21, 4103.
and leaf morphophysiological characteristics of European hackberry (Celtis australis) seedlings. Chem. Biol. Technol. Agric. 7, 9.

39. Jones A.S., Marinia J., Solo-Gabrielea H.M., Robey N.M. and Townsend T.G. 2019. Arsenic, copper, and chromium from treated wood products in the U.S. disposal sector Waste Management, 87(15), 731-740.

40. Juniar, L., Mariana, S., Mulyati, D., Fathira, and R Safitri. 2020. Preparation and Characterization of Activated Carbon from Gayo Coffee Shell as an Adsorbent for Removal of Lead (Pb) in Liquid Waste IOP Conf. Series: Materials Science and Engineering, 796, 012050.

41. Kalagbor, I.A., Amalo, N., Dibofoiri-Orji, and Ekpete, O.A. 2019. Exposure to Heavy Metals in Soot Samples and Cancer Risk Assessment in Port Harcourt, Nigeria J Health Pollut, 9(24), 191211.

42. Khalife, K.C. and Matsuura, T. 2018. Removal of heavy metals and pollutants by membrane adsorption techniques. Applied Water Science, 8, 19.

43. Kim H.S., Kim Y.J., and Seo Y.R. 2015. An Overview of Carcinogenic Heavy Metal: Molecular Toxicity Mechanism and Prevention J Cancer Prev. Dec; 20(4), 232–240.

44. Kloch, M. and Mamińska, R.T. 2020. Toward optimization of wood industry wastewater treatment in microbial fuel cells – mixed wastestreams approach. Energies, 13(1), 263.

45. Kwon S., Fan M., Herbert F.M., Armistead D, Kathryn G.R, Berchtold A. and Manvendra K.D., 2011. Coal Gasification and Its Applications Chapter 10 - CO2 Sorption, 293-339

46. Latif J., Akhtar J., Ahmad I., Rehman M. M, Shah G.M., Zaman Q., Javed T., Farooqui Z.U.R., Shaker M., Saleem A. and Rizwan M. 2020. Unraveling the effects of cadmium on growth, physiology and associated health risks of leafy vegetables Brazilian Journal of Botany, 43, 799–811.

47. Lee, X. J., Hiew, B. Y. Z., Lee, L. Y., Gan, S., Gopakumar, S.T. 2017. Evaluation of The Effectiveness of Low-Cost Adsorbents from Oil Palm Wastes for Wastewater Treatment Chemical Engineering Transactions, Vol. 56.

48. Lim, Y.H., Chew, I.M.L., Choong, T.S.Y., Tan, M.C., Tan, K.W. 2016. Nanocrystalline cellulose isolated from oil palm empty fruit bunch and its potential in cadmium metal removal, MATEC Web of Conferences, 59, 5.

49. Azemi M., Noor M., and Sarip H. 2000. Oil Palm (Elaeis guineensis) Wastes as a Potential Source of Cellulose.Cellulosic Pulps, Fibres and Materials Cellucon ’98 Proceedings, 13-17.

50. Mamińska, R.T. 2020. Wood-Based Panel Industry Wastewater Meets Microbial Fuel Cell Technology. International Journal of Environmental Research and Public Health; 17(7), 2369. https://doi.org/10.3390/ijerph17072369

51. Mahmudi, M., Arsad, S., Amelia, M.C., Rohmaningsih, H.A. and Prasetya, F.S. 2020. An alternative activated carbon from agricultural waste on chromium removal. Journal of Ecological Engineering, 21(8), 1-9.

52. Malaysian Oil Palm Board (MPOB) 2019. Extracted from http://bepi.mpob.gov.my

53. Marsin, F.M., Ibrahim, W.A.W., Nohem, Suitirman H.R.Z.A., and N.N. Ting 2018. Recent Advances In The Preparation of Oil Palm WasteBased Adsorbents for Removal of Environmental Pollutants - A Review Malaysian Journal of Analytical Sciences, 22(2), 175–184.

54. Mathew, B.B., Jaishankar, M., Biju, V. G. and Beeragowda K.N. 2016. Role of biosorbents in reducing toxic metals. Journal Toxicology, 12, 1–13.

55. Melia, P.M., Busquets, R., Santanu, R. and Andrew, B.C. 2018. Agricultural wastes from wheat, barley, flax and grape for the efficient removal of Cd from contaminated water RSC Adv., 8, 40378–40386.

56. Milan, K. 2014. Adsorption, chemisorption, and catalysis. Chemical Papers. 68.

57. Negm, N., Ali, H.H. and Abd-Elaal, A. 2017. Project: Assessment of Agricultural Wastes as Biosorbents for Heavy Metal Ions Removal from Wastewater Surfactants in Tribology, Vol. 5.

58. Obayomi, K.S., Bello, J.O., Nnoruka, J.S., Adediran A.A and Olajide, P.O. 2019. Development of low-cost bio-adsorbent from agricultural waste composite for Pb(II) and As(III) sorption from aqueous solution, Cogent Engineering, 6, 1.

59. Othman, Z., Habil, M. and Hashem, A. 2012. Removal of Zinc(II) from aqueous solutions using modified agricultural wastes: kinetics and equilibrium studies. Arabian Journal Geoscience, 6, 4245–4255.

60. Ooia, S.L. and Ong, S.T. 2019. Remediation of Lead (II) And Malachite Green from Aqueous Solution Using Palm Oil Fruit Fibre Studia Ubb Chemia, Lxiv, 4, 55-70.

61. Patel, H. 2019. Fixed-bed column adsorption study: A comprehensive review. Applied Water Science 9, 45.

62. Pavelková, M., Vysloužil, J., Kubová, K., Vetchý, D. and Slov, C. 2018. Biological role of copper as an essential trace element in the human organism Farm. Winter; 67(4), 143-153.

63. Pyrzynska, K. 2019. Removal of cadmium from wastewaters with low-cost adsorbents Journal of Environmental Chemical Engineering 7, 102795.

64. Rahman, M.M., Adil, M., Yusof, A.M., Kamaruzzaman, Y.B. and Ansary R.H. 2014. Removal of Heavy Metal Ions with Acid Activated Carbons Derived
Shahrkia, R.S., Benally, C., El-Din, M.G. and Par-

Sevim, C., Dogan, E. and Comakli, S. 2020. Cardio-
vascular disease and toxic metals Current Opinion in Toxicology, 19, 88–92.

Saxena, J., Rawat, J. and Kumar, R. 2017. Conversion of Biomass Waste into Biochar and the Effect on Mung Bean Crop Production. Clean Soil Air Water, 45, 1501020.

Sevim, C., Dogan, E. and Comakli, S. 2020. Cardio-
vascular disease and toxic metals Current Opinion in Toxicology, 19, 88–92.

76. Shahراكia, R.S., Benally, C., El-Din, M.G. and Park-ka, J. 2021. High efficiency removal of heavy metals using tire-derived activated carbon vs commercial activated carbon: Insights into the adsorption on mechanisms Chemosphere, 264, Part 1, 128455.

Sims, R.A., Harmer, S.L. and Jamie S. Quinton, J.S. 2019. The Role of Physiosorption and Chemisorption in the Oscillatory Adsorption of Organosilanes on Aluminium Oxide Polymers, 11(3), 410.

Siyal, A.A., Shamsuddin, M.R., Low, A., and Rabat, N.E. 2020. A review on recent developments in the adsorption of surfactants from wastewater. Journal of Environmental Management, 254, 109797, https://doi.org/10.1016/j.jenvman.109797.

Sudaryanto, Y. 2006. High surface area activated carbon prepared from cassava peel by chemical activation. Bioreosour.Technol., 97(5), 734–739.

80. Thuan, T.V., Quynh, B.T.P., Nguyen, T.D., Ho, V.T.T. and L.G. Bach, 2017. Response surface methodology approach for optimization of Cu2+, Ni2+ and Pb2+ adsorption using KOH-activated carbon from banana peel, Surfaces and Interfaces. Surfaces and Interfaces, 6, 209-217.

81. Tobi A.R., Dennis J.O., H.M. Zaid, A.A. Adekoya, A Yar, and U. Fahad 2019. Comparative analysis of physiochemical properties of physically activated carbon from palm bio-waste, Journal of Materials Research and Technology, 8(5), 3688-3695.

82. Vakili, M., Rafatullah, M., Ibrahim, M.H. Abdullah A.Z. and Gholami 2014. Reviews of Environmental Contamination and Toxicology Reviews of Environmental Contamination and Toxicology 61, 232.

83. Vinaykumar S N, Basavaraj C.R, and Prakash B. A. 2005. Removal of Cadmium from Electroplating Industrial Waste Water using Natural Adsorbents International Research Journal of Engineering and Technology (IRJET) 6, 5.

84. Wang, J.L. and Chen, C. 2009. Biosorbents for heavy metals removal and their future Biotechnology Advances, 27, 2, 195-226.

85. Yeow, P.K., Wong, S.W., and Hadibarata, T. 2021. Removal of azo and anthraquinone dye by plant biomass as adsorbent – A Review, 11(1), 8218-8232.

86. Yunus, Z. M., Gopalakrishnan Y ., Adel A.G., Othman N., Hamdan R., Nurun R. 2020. Advanced methods for activated carbon from agriculture wastes; A comprehensive review. International Journal of Environmental Analytical Chemistry. DOI: 10.1080/03067319.2020.1717477.

87. Yunus, Z., Othman, N., Al-Gheethi, A., Hamdan, R. and Nurun, R. 2019. Adsorption of heavy metals from mining effluents using honeydew peels activated carbon; isotherm, kinetic and column studies. Journal of Dispersion Science and Technology. DOI: 10.1080/01932691.2019.1709493.

88. Zhu, Y., Fan, W., Zhou, T. and Li, X. 2019. Removal of chelated heavy metals from aqueous solution: A review of current methods and mechanisms Science of the Total Environment 678, 253–266.