Life cycle assessment approach to sustainable sewage sludge management for water pollution control

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Abstract. Increase in population growth coupled with industrialization, urbanization and requirements for implementation of stricter effluent discharge standards, sludge from wastewater treatment plants (WWTP) is expected to be produced in a continually increasing amount globally. The management of the huge volume of sludge generation becomes an integral component of environmental sustainability. Therefore, the need for environmentally friendly approach to sludge management strategy couldn’t be overemphasized. This paper proposes a rational and more sustainable approach directed towards devising means to solve the problem of the huge amount of WWTPs sludge by converting it to granular activated carbon (GAC) for utilization in water pollution control via incorporating Life Cycle Assessment (LCA). The paper reviews the various approaches and techniques for drying, pyrolysis and activation techniques and the best operating conditions for sludge based activated carbon (SBAC) for optimal pollution control. Based on that, a holistic decision making tool was recommended which incorporates major production, treatment and disposal options for each stage using Life Cycle Assessment (LCA) approach (from-cradle-to-grave), from which wide range of alternative scenarios will be generated vis-à-vis water pollution control efficacy in relation to environmental, cost as well as energy implications.

1. Introduction

Activated sludge system (ASC) is biological process which is the key wastewater treatment processes with more than 90% of the domestic wastewater treatment plants (WWTPs) employing it. ACS degrades mainly, the biodegradable components in the wastewater into solid mass (sludge). Global continual increase in inhabitants and industrial activities implies that the generation of sludge will be dramatically increasing in most communities [1-4]. Additionally, about 25–65% of the overall operational cost of a secondary WWTPs go for sludge management which include dewatering, treatment and final disposal [2]. Although there exists a number of sewage sludge management alternatives [5], yet recent stringent regulations due to environmental concerns [6, 7] rendered current management alternatives less attractive [4]. Thus the importance of devising for more environmentally friendly alternative cannot be overemphasized. One of the most promising popular option in this regard is using sludge as a raw material for production of adsorbents in form of granular activated carbons (GAC) and their subsequent utilization in pollution control [8]. GAC have been widely accepted as adsorbents due to their excellent exhibited uptake capacities for effective decontamination of air containing harmful substances, water and wastewater. Their effectiveness have established to the achievable high effluent quality, abundant of raw materials, design simplicity, operation easiness and its compatibility for uptake of wide range of...
pollutants. In spite of these GAC merits, commercial GAC are still expensive, especially for deployment at industrial scale. Therefore, in the last few decades, researchers have dissipated great efforts towards production of GAC from different materials in include agricultural by-products and waste materials. Owing to the rich carbonaceous content of WWTP sludge, production of GAC from WWTP sludge attracted increased attention in recent years. Hence, as a catalyst to ensuring environmental sustainability, production of GAC from WWTP sludge is expected to offset expenditure associated with sludge disposal, beside the end product having additional potential applications in control of environmental pollution. Smith et al. [8] and Mu’azu el. al. [4] have reported comprehensive reviews on published works related to production of GAC produced from WWTP sludge and their subsequent applications for wastewater and water pollution control. These papers present a good collection of data and information on the topic for comparison purposes and further recommend in cooperating economic viability through re-evaluation and assessment with context of sustainability especially, for deployment of the sludge based GAC on an industrial scale.

In recent years, production of sewage sludge based GAC and its utilization in pollution control has been an area of research due to their been attractive cost-effective alternative for sewage sludge management option. Owing to the fact that each of the steps to be taken in this regard involves wide range of alternative options, this may render the apt decision and or direction to follow in each stage not a straightforward issue. In other words, the key involving processes such as dewatering of the sludge, activated carbon production and the treatment are interrelated activities as they may influence one another whether at the upstream or downstream direction. Moreover, the environmental impacts and associated economics considerations of different combinations of the alternative processes are most likely not to be the same. Consequently, the stand-alone approach to the various involving processes which is the “business as usual” approach adopted by all previous researches and practices could no longer be viable due to the recent intense demand for meeting environmental sustainability.

This paper proposes a viable and sustainable means of solving environmental problems associated with the huge amounts of sludge generated from wastewater treatment plants (WWTPs). It proposes converting WWTP sludge into granulated activated carbon (GAC) that could be used in decontamination of the industrial wastewater containing toxic substances via introducing LCA into the whole processes involved as a yardstick for sustainability assessment. The expected result is creation of a holistic decision making tool which incorporates different production, treatment and disposal techniques as options for each stage from which wide range of alternative scenarios will be generated vis-à-vis associated environmental impacts, energy and cost implications.

2. Life Cycle Assessment (LCA)
Life Cycle Assessment has been defined as “an objective process to evaluate the environmental burdens associated with a product, process or activity, by identifying and quantifying materials and energy used and waste released to the environment, and to evaluate and implement opportunities to effect environmental improvements”[9]. Thus, LCA is a methodology to examine a product, process or service in relation to its associated environmental impacts via cradle-to-grave approach[9]. This include in cooperating from the stage of the raw materials acquisition down to the final disposal and all the associated costs implications as well as environmental impacts and any waste released along the chain. LCA uniquely accounts of relevant issues not captured via employing other environmental management tools such as statutory environmental impact assessment [9-11]. Application of LCA in integrated solid waste management, generally, constitutes another field of application supporting decision makers, planners and industries in apt management and selection amongst alternatives options for achieving cost-effectiveness and overall sustainable operations [12]. As presented in Figure 1, LCA is generally, undertaken in four stages. These include: goal definition, next is the inventory analyses which form the final stage of the LCA. A generalized LCA schematic for a production system is illustrated in Figure 2. A
A general principle in LCA is that, more critical the target material or a process is, the more vital to acquire and conduct an accurate life cycle inventory (LCI) analysis data as shown in Figure 3.

Figure 1. LCA frame work main components and its Applications[9].

Figure 2. Life Cycle Assessment Approach
3. Techniques for LCA data collection

The process of GAC production from sewage sludge generally consists of dewatering, drying and production via activation to transform the raw material into the GAC. The various processes as well as the techniques involved from which data can be collected for performing the LCA are reviewed below.

3.1 Procurement, Dewatering and Drying of Sewage Sludge

Dewatering is the first stage in raw WWTP sludge processing which produces sludge cake via transformation of the raw sludge from a liquid/slurry form to a solid waste. Belt presses, vacuum filters and centrifuges are the commonly employed dewatering processes by WWTP. Literature reviews indicated that filter presses and centrifuges are the most efficient dewatering techniques compared to vacuum filters and they are capable of yielding up to 35% of total solid concentrations (Table 1)[4, 8]. Dewatered and dried secondary sludge from different wastewater treatment plants employing distinct dewatering techniques may differ in terms of carbon content richness and some characteristics for the produced sludge. Moreover, the distinct techniques would have different in terms of impact on efficiency, energy expenditure well as material consumption. Thus, collectively with the characteristics of the sludge would influence the best choice for the sludge dewatering when detailed LCA is conducted for via taken in cognizance the different dewatering techniques.

3.2 Pyrolysis of Dried Sludge to Produce Char

Dewatered sludge then undergoes pyrolysis via application of heat in order to reduce the water content and render it drier via evaporating the water below the moisture content not achievable during dewatering process [9]. Usually, besides drying, sewage sludge pyrolysis is undertaken under inert atmosphere at 400-1000 °C to enable releasing volatile compounds and to produce char [13, 14]. The characteristics (i.e. BET surface area and pore volume) char produce in this process depends on the operational temperature and pyrolysis duration (Table 2). Different studies suggested different optimal temperature[14, 15] and dwell time[16] for maximizing the important adsorptive physical characteristics of the produced GAC such as pore volume BET surface area and yield.
### Table 1. Total solid content after sludge dewatering [4, 8] [7].

| Treatment   | Source of sludge          | Total solids (%) |
|-------------|---------------------------|------------------|
| Centrifuge  | Activated sludge          | 14-20            |
|             | Anaerobic digester        | 15-35            |
|             | Aerobic digester          | 8-10             |
| Vacuum filter| Activated sludge      | 12-18            |
|             | Anaerobic digester (mixture) | 17-23        |
| Belt press  | Activated sludge          | 12-18            |
|             | Anaerobic digester (mixture) | 17-23        |
|             | Anaerobic digester        | 12-30            |
|             | Aerobic digester          | 12-25            |
| Filter press| Activated sludge          | 27-33            |
|             | Anaerobic digester (mixture) | 29-35        |

### Table 2. BET surface area chemically activated sludge based GAC produced [4, 8][7]

| Activation agent | Agent/sludge ratio | Temp (ºC) | Dwell time (min) | BET surface area (m²/g) |
|------------------|--------------------|-----------|------------------|-------------------------|
| KOH              | 1:1                | 700       | 60               | 1882                    |
| KOH              | Soaked in 3M       | 600       | 60               | 382                     |
| KOH              | KOH                | 700       | 60               | 1686                    |
| KOH              | 3:1                | 700       | 60               | 1301                    |
| NaOH             | 1:1                | 700       | 60               | 1224                    |
| ZnCl₂            | 3:1                | 500       | 2                | 647                     |
| ZnCl₂            | 10 g in 25 ml 5M   |           |                  |                         |
| ZnCl₂            | ZnCl₂              | 800       | 120              | 1092                    |
| ZnCl₂            | 3.5:1              | 650       | 5                | 472                     |
| H₂SO₄            | 1:1                | 650       | 60               | 408                     |
| H₂PO₄            | 3M H₂SO₄           | 650       | 60               | 289                     |
| H₂PO₄            | 100 g in 250 ml 3M |           |                  |                         |

### 3.3 Physical and chemical activation of char

The char produced at the pyrolysis stage can be activated, mainly, via two methods; physical and chemical activation techniques. Physical activation proceeds by the progressive burn-off of the carbon fraction of the char using gasses [11]. As the inorganic content of sludge is high, the resulting GAC relatively, exhibits lower BET surface area [7]. The characteristics (i.e. yield, BET surface area and pore volume) of the produced GAC are influenced by activating gas employed, temperature and the activation process dwell time. Different activating gases, air[17], CO₂ [18, 19] and steam [20], were studied. Data, regarding BET surface area, suggest that steam is the best physical activation gas. As high as 226 m²/g BET surface area was achievable [20, 21]. Statistical optimization modeling approach employed maximized the BET surface area at an activation condition of 763 oC and about 40 minutes dwell time. In contrast, the optimal conditions for the pore volume were obtained at 70 minutes and temperature of 790 oC [20, 21]. For a sludge activated physically, washing the char with HCl before activation resulted
in an dramatic increase in BET surface area from 7 to 269 m²/g [18]. Thus, novel approaches to physical activation may merit further investigations [8].

Sludge based GAC physical characteristics produced via chemical activation are basically, influenced by: chemical agent/activator used, activating time activator/sludge ratio and temperature[8]. Different chemical reagents were used such as: KOH, NaOH, ZnCl₂, H₂SO₄ and H₃PO₄ [4]. Table 2 shows that the most effective reagents are NaOH, ZnCl₂ and KOH reported [4]. However, different pyrolysis, pretreatments and post-treatments were employed in these studies. To the best of our knowledge, reports on research systematic comparative study on efficacy of these activating agents is deficient in literature. The general rule is that optimum temperature is related to time of activation with higher temperature requiring lesser activation time. There is no published or sufficient literature about optimizing yield in relation to the physical characteristics of the produced sludge GAC. As such, optimizing the operating conditions using optimization technique such as response surface methodology during the activation of the char to produce the best GAC to ensure higher adsorptive performance for sorption of target pollutant(s) is recommended.

4. Adsorption of liquid phase pollutants by SBACs
Assessment of SBAC performance in water pollution control is achieved by investigating effect of operational parameters, kinetics, thermodynamics as well as equilibrium and approaches using batch shake-flask experiments. Data from these experiments could indicate the maximum capacity of the sludge GAC for the target adsorbate(s) in the aqueous phase. Moreover, breakthrough curves produce using fixed-bed column experiments conducted to provide changes in concentration of the adsorbate with time at different operating conditions. Some studies demonstrated that GAC produced with sludge as raw materials have the potentials for yielding higher adsorptive performances exceeding that of commercial activated carbon[22].

4.1 Regeneration of spent activated carbon
One of the key merits of using sludge based GAC is the financial benefits associated with its potential recycling of spent GAC via regeneration/reactivation and subsequent reuse. In this manner, the operating cost could be reduced by up to 20-40% less than the cost of production of the original GAC [4, 8]. Consequently, reactivated of spent GAC is considered recovered resource. Alternatives that can be used for sludge GAC regeneration include, heating in a rotary kiln or open-hearth furnace and washing with dilute acids. Considering that washing spent GAC with acids can introduce impurities on the regenerated GAC [22], it is recommended to fully characterize regenerated SBAC prior to reuse.

5. LCA for SBAC Production and its Utilization water pollution control
Figure 4 provides a simplified LCA for the production of SBAC and its usage for water and wastewater decontamination, indicating the system boundary and describing the relation between involving processes. A general principle in LCA is the more important a material or a process is, the more important it is also to get adequate and reliable inventory data (LCI) about the different components in the material production involving processes. In an anticipatory way, production data SBAC shall be based on precise and comprehensive information from experiments and analyses conducted during the study as LCI data with a high level of representativeness. The inventory will encompass all the material and energy inputs on one hand, and materials output, generated wastes and emissions as well as their energy values. Based on the data gathered in conjunction with employing existing models and data in the literature, detailed LCA could be conducted using softwares such as SIMAPRO. SIMAPRO, for example, have the capacities for comprehensive analyses of the environmental aspects and associated economics considerations of different combinations of the alternative processes and techniques mentioned earlier according to Figure 1. Hence, the pros and cons of each option selected amongst the various alternatives under investigation in each stage could be evaluated vis-à-vis the environmental and economic considerations in terms of amount of energy used in the process, Amount of CO₂ equivalent generated, Materials consumptions and overall process efficiencies.
6. Conclusion

This paper reviews the different techniques employed for conversion of WWTP sludge in activated carbon. It proposes a more sustainable approach for the selection between various alternatives during production of sludge based activated (SBAC) from wastewater treatment plant sludge. The approach entails the utilization of capabilities of life cycle assessment (LCA) technique in the production as well as in the application in removal pollutants from water and their subsequent regeneration/recuse from a holistic point of view. LCA modeling based on the LCI datasets should be based on pre-selected softwares such as SimaPro software that will help in calculation the CO2 equivalents of the whole process from production until disposal of the materials. The paper also underscores the relevance of understanding the different processes for ensuring accurate and sufficient data inventory both from experiments, existing models and data in the literature for reliable analyses. Hence, the apt management of the huge volume of sludge in current and future generation via LCA could in go a long way becoming and integrated component of environmental sustainability.

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