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Research article

Development of oil-spill sorbent from straw biomass waste: Experiments and modeling studies

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A B S T R A C T

The recovery of oil spilled on land or water has become an important issue due to environmental regulations. Canadian biomasses as fibrous materials are naturally renewable and have the potential to absorb oil-spills at different ranges. In this work, four Canadian biomasses were examined in order to evaluate their oil affinities and study parameters that could affect oil affinity when used as sorbent, such as average particle size, surface coating and reusability. Moreover, one oil sorption model was adopted and coupled with another developed model to approximate and verify the experimental findings of the oil sorbent biomasses. At an average particle size of 150–1000 μm, results showed that barley straw biomass had the highest absorbency value at 6.07 g/g, while flax straw had the lowest value at 3.69 g/g. Wheat and oat straws had oil absorbency values of 5.49 and 5.00 g/g, respectively. An average particle size of 425–600 μm indicated better absorbency values for oat and wheat straws. Furthermore, the thermal stability study revealed major weight recovery for two flame retardant coatings at hemicellulose and lignocellulose degradation temperature ranges. It was also found that oat straw biomass could be regenerated and used for many sorption/desorption cycles, as the reusability experiment showed only a 18.45% reduction in the oil absorbency value after six consecutive cycles. The developed penetration absorbency (PA) model showed oat straw adsorbed oil at the inter-particle level; and, the results of the sorption capacity model coupled with the PA model excellently predicted the oil sorption of raw and coated oat straws.

1. Introduction

The recovery of spilled oil resulting from the production or transportation of oil commands serious attention. Many related accidents have occurred, with frustrating results. In April 2010, the Gulf of Mexico experienced underwater oil rig explosion that left behind a huge oil spill with an estimated total oil leakage of 4.5 million barrels (Quintana-Rizzo et al., 2015). The impact of this spill on the Gulf of Mexico marine life is still under investigation by many researchers. However, many of the marine life were lost due to the pollution and toxicity of the spill (Bozeman, 2011). Later, evidences showed that the losses in the marine life could be related to the spill (Balmer et al., 2015).

Sorbents are materials that have the affinity to sorb, evenly distribute and trap liquid oil within their unique structure. Scientists have begun to develop sorbents for different separation processes, such as liquid/liquid and liquid/solid separations (Chatterjee and Gupta, 2002). The general uses of sorbents have been considered for control and treatment of environmental pollution.

With the growing number of oil sorbents, the selection of the proper sorbent is essential to ensure maximum oil recovery. Oil sorbents can be classified into minerals, synthetics, and organics naturals. Mineral sorbents can be used for spilled oil fields: exfoliated graphite, as an example, can be used for land oil recovery and the removal of oil from water. Synthetics sorbents are well known in spilled oil recovery, due to their high oil absorbency values and their ease of modification. Organic natural sorbents are materials that grow or present naturally. One example of organic natural sorbents is biomass, which is also defined as agricultural waste. Each oil sorbent category has its own benefits: for example, synthetic organic sorbents tend to have relatively low bulk density compared to inorganic mineral sorbents, and biodegradability is mostly associated with organic natural oil sorbents (Chatterjee and

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Gupta, 2002).

Lignocellulosic straws, such as wheat, oat, flax and barley, are considered biomasses. These straws are mainly comprised of carbon (C), hydrogen (H), oxygen (O) and nitrogen (N) in the forms of cellulose, hemicellulose, and lignocellulose (Aqsha et al., 2014). Although many researchers have attempted to convert biomasses into different sources of energy, very few studies have reported their usage as sorbents for oil spills.

Parameters that can be measured to assess straw biomass oil sorption effectiveness are the average particle size, surface coating, oil selectivity and sorbent structure. The average particle size of oil sorbent is used to differentiate the dimensions of sorbent particles. Particle size may affect the oil sorption capability, since the force that drives the oil inside the sorbent particle is capillary force. Surface coating is a modification that can be done on a sorbent surface to protect it and increase its oil sorption capacity.

Different methods can be employed to assure optimal oil recovery results. For example, selection of the optimal average particle size and the optimal surface coating, while maintaining a satisfactory moisture content condition, can maximize the oil sorption capacity.

Although the selection of an appropriate biomass average particle size impacts the overall oil sorption capacity, there have been very few studies. Li et al. (2013) reported that the average particle size of 830–1700 μm had the highest diesel sorption capacity for sawdust and corn stalk and 380-55 μm for wheat straw biomass. Peng et al. (2013) found the optimal average particle size for crude oil sorption capacity of cellulosic modified corn stalk biomass to be 250–850 μm.

Many researchers have conducted surface modifications for different sorbent types. However, the effects of the added chemicals on enhancing oil affinity and reducing the water uptake ratio have rarely been reported (Wang et al., 2013). Modification of kapok fiber using five solvents to enhance the oil absorption process was reported by Wang et al. (2012a).

The oil selectivity of sorbents has commanded the attention of researchers due to the spills that happen on water. The process of cleaning up spills on water requires highly selective oil sorbents. The study of polymer-coated kapok biomass was conducted where raw and polymer-coated kapok showed similar oil sorption capacities for pure oil or oil mixed with synthetic seawater (Wang et al., 2013). Li et al. (2013) reported that the oil/water system absorbency values for corn stalk and wheat straw were similar to those with oil only (7.02 and 8.54 g/g, respectively), while sawdust had a 1.5% lower oil absorbency when an oil/water system was used. Wooden chip biomass (cellulosic fiber) was also examined for oil uptake from water: and, a high oil sorption capacity of 5 g/g was reported when Iranian heavy crude oil was used rather than light cycle and light gas oils (Teas et al., 2001).

One of the most vital processes in the cleanup of spilled oil is the industrial regeneration of sorbents. The purpose of this process is the recovery/reclamation of the oil and/or sorbent. A reduction in the oil sorption capability of biomass-like materials can result from the deterioration of the sorbent's internal structure after several oil sorption/desorption cycles; however, the reduction percent is highly dependent on the desorption method (Wang et al., 2013; Wang et al., 2012b). Wang et al. (2012a) reported reductions in oil sorption capability of 10, 17.39, 25, 24.86 and 28.61% after the eighth cycle for raw and treated kapok fiber with water, hydrochloric acid, sodium chlorite and chloroform, respectively. A decrease in the oil sorption capacity of poly(butyl methacrylate) (PBMA) and polystyrene (PS) coated kapok fibers using diesel and soybean oils was also observed (Wang et al., 2013), where more than 90% of oils were removed within six cycles.

To facilitate the understanding of the general mechanisms involved in the liquid absorption process, theoretical approaches should be both applied and verified. By assuming kapok fiber as bundles having unvarying circular vessel pore distributions, Dong et al. (2014) developed a dual-scale oil penetration model to predict and compare the oil sorption coefficients at different kapok packing densities. Washburn's equation for liquid flows in capillaries was considered; however, the intra-sorption phenomenon (within fiber lumens) was emphasized as the more dominant phenomenon within kapok fiber.

Different liquid absorption theoretical approaches have been studied. Dias and Delkumburewatte (2009) applied Hagen–Poiseuille's principle and the Lucas–Washburn equation to estimate the wetted capillary length 'knitted spacer' water absorption; and, Rotaru et al. (2014) built empirical models to assess the experimental result that would be beneficial in optimizing the production of aerogel clay polymer composites as sorbents. Das et al. (2012) equalized the capillary action and gravitational buoyancy forces in order to develop a model describing the liquid absorption phenomena within nonwoven materials.

Although oil sorption capacity plays an important role in selecting the proper oil sorbent, other parameters may facilitate or repel the sorption capacity. Therefore, this study evaluated straw biomasses for their oil sorption capability by manipulating different parameters that can affect the oil sorption capacity. Four different average particle sizes were chosen to obtain information regarding the effects of particle size. The effects of moisture content and surface coating for the straw biomass were experimentally correlated to the oil sorption capacity. Experiments were made to increase the oil selectivity of straw biomass over water and seawater as well as its reusability. Two models sorption capacity (SC) and penetration absorbency (PA) were used and verified with some experimental findings to gain a better understanding about the oil sorption phenomenon.

Previous studies were limited only to experimental investigation of biomass in the oil spill cleanup. This work fills the gap by integrating the modeling and theoretical finding to new sets of experimental data in order to obtain a clear understanding of the mechanisms involved in the use of biomass in oil spill cleanup. Therefore, the objectives of this work were: (1) the provision of a thorough understanding and evaluation of the sorption capability of biomass in the area of oil-spill recovery while manipulating different parameters that could enhance the oil recovery process: and, (2) evaluation of the proportion of liquid oil within and between particles since, to the best of our knowledge, no study has been made to estimate the intra-particle and inter-particle oil sorption for oat straw biomass. The purpose was the acquisition of information that could help during the wetted oat straw desorption process.

2. Materials and methods

2.1. Materials

The following materials were used: four agricultural waste biomasses (wheat, oat, barley and flax straws from a farm in Saskatchewan, Canada), InstaZorb (commercial sorbent), non-detergent motor oil (SAE 30), two flame retardant sprays; Excel Fire Retardant (F.R.1) and Escort Fire Retardant Silicon Waterproofing (F.R.2), and distilled water.

All the agricultural waste biomasses were received in carton boxes that contained pure straws (free of grain and other contaminants). Each biomass was milled using a Blendtec grinder. The samples were then sieved using a sieving machine into an average particle size of 150–1000 μm for comparison of each biomass and into different average particle sizes of 212–425 μm, 425–600 μm,