Cellulose
DOI 10.1007/s10570-014-0203-9

ORIGINAL PAPER

Utilization of rice husks for the production of oil sorbent materials

Alireza Bazargan · Jun Tan · Chi Wai Hui · Gordon McKay

Received: 31 October 2013 / Accepted: 13 February 2014

Abstract Rice is the third largest cultivated cereal crop in the world, making rice hulls one of the most abundant biowastes on Earth. In this manuscript, the rice husks have been subjected to alkali treatment at low temperatures aiming to produce a lignocellulosic sorbent material as well as removing their silica. This absorbent has been subsequently tested for marine diesel spill clean up. Various treatment conditions such as NaOH concentration, duration, and temperature have been investigated. The optimized cellulosic sorbents show high RMG380 marine diesel uptake due to low bulk density and their fluffy structure. It is argued that the bulk density is a critical factor in the excellent uptake capacity. As far as the authors are aware, these results (as high as 20 g of RMG380 sorbed per gram of sobent) show the highest oil sorption for rice husk derived materials reported in literature. Other advantages include higher yields and lower treatment temperatures compared to other studies. The proposed cheap and environmentally friendly method provides a simple and safe technique for the production of valuable products from lignocellulosic agricultural waste.

Keywords Rice husk/hull/chaff · Oil spill clean up and remediation · Marine diesel · High capacity sorbent · Adsorbent

Introduction

Rice is an annual cereal plant which completes its entire life cycle from planting to harvesting within a single year. The husk (also known as the hull or chaff) is the protective outer layer of the grain containing large amounts of silica. About 20 % weight of the rice is disposed as husk (Kumagai et al. 2007). The exact composition of rice husk is highly dependent on many variables, most of which cannot be controlled such as the weather conditions (Van Nguyen and Ferrero 2006; Sweeney and McCouch 2007; Peter Rosner and McCulloch 2008; Peng et al. 2009; Stoop et al. 2009; Malekmohammadi et al. 2011). Annually about 200 million tons of rice is produced in China alone. India and Indonesia are the second and third largest rice

---

A. Bazargan (✉) · J. Tan · C. W. Hui · G. McKay
Department of Chemical and Biomolecular Engineering,
Hong Kong University of Science and Technology,
Clearwater Bay, Hong Kong
e-mail: bazargan@ust.hk

J. Tan
e-mail: jtanaa@ust.hk

C. W. Hui
e-mail: kehui@ust.hk

G. McKay
e-mail: kemckayg@ust.hk

Present Address:
A. Bazargan
Department of Chemical Engineering and Biotechnology,
University of Cambridge, New Museums Site, Pembroke
Street, Cambridge, UK

producers respectively. Rice is currently the third most widely produced crop in the world (700 million tons/year) standing behind sugar cane and maize (Khush 2005; FAOSTAT 2013a). In the past decade the production of paddy rice has increased by approximately 2.3 % (FAOSTAT 2013b). Rice hulls have a low percentage of protein and available carbohydrates, and a high percentage of crude fiber, crude ash, and silica (Hirotsu et al. 2007; Kamoshita 2007; Naing et al. 2008; Talpur et al. 2011). Rice husks have a low content of digestible nutrients (<10 %). Silica content has been reported at 12.4–22.9 % with the mean of 18.6 % in the dry season and 10.9–20.8 % with the mean of 15.4 % in the wet season (Juliano 1985). Various applications for rice husks have been suggested (Safa and Bhatti 2011a, b; Kamsonlian et al. 2012; Mehdinia et al. 2013; Lordan et al. 2013; Hongo et al. 2013; Pereira et al. 2013).

On the other hand, oil spills are a serious environmental threat that might take years or even decades to clean up. The detrimental effects of spills are not only limited to direct effects on coastal ecosystems, human health, and marine life, but also the indirect and chronic ones. Further study of regions prone to oil spills shows the necessity of establishing protocols for emergency operations (Asfad and Darabinia 2013). Susceptible areas of the world such as the Persian Gulf have been frequently studied [although some have incorrectly referred to the Persian Gulf with false names such as “the Persian-Arabian Gulf”, the “Arabian Gulf”, or just merely the “Gulf” (Elhakeem et al. 2007; Verma et al. 2008; Kirby and Law 2008) in contrast with the United Nations’ assertion against the use of such fabricated names (United Nations Group of Experts on Geographical Names 2006)].

Various methods such as mechanical, chemical, physicochemical, and biological can be applied for combatting oil spills and the use of dispersants, absorbents, solidifiers, booms and skimmers are common (Adebajo et al. 2003; Deymeh et al. 2012; Seyedi et al. 2013). Some studies suggest that large spills are first handled by trying to restrict the dispersion of the oil with booms, followed by collection of the oil with skimmers. The remaining oil which washes onto shores is mechanically collected either by suction or shovels. Sorbents are often applied for small-scale spills (Suni et al. 2004). To date, hundreds of different types of materials, including natural and synthetic ones have been tested as possible sorbents (Adebajo et al. 2003; Suni et al. 2004; Sayed and Zayed 2006; Rajakovic et al. 2007; Rajaković-Ognjanović et al. 2008; Wahi et al. 2013). The type of petroleum product which is spilled is also of importance. Some can be flushed or cleaned up with porous surfaces, some are prone to weathering and evaporation of volatile components, and some sink to the bottom of the sea. The un-sunk fraction will form slicks that pollute rocky and sandy coastlines such as beaches, ports, wharfs, marinas, caves, historic and touristic sites, and nature reserves (El-Fadel et al. 2012).

Several studies have used rice husks as possible sorbent materials for oil spills. About a decade ago, a Japanese study reported the absorption of oil by carbonized rice husk (Kumagai et al. 2007). The husk was pyrolyzed in a vacuum (500 Pa) at 300–800 °C after pretreatment with steam and refining. A maximum uptake capacity of 6.7 g heavy oil/g as-prepared husk was obtained. In a Nigerian study (Nwankwere et al. 2010), rice husks were acetylated using N-bromosuccinimide (1 % NBS) as a catalyst. Acetylation for 1 and 3.5 h can increase the crude oil sorption from 1.9 g/g to 8.2 and 10.3 g/g, respectively. Bulgarian researchers have also published several papers in recent years, sometimes very similar, regarding oil absorption onto heat-treated rice husks (Angelova et al. 2011; Vlaev et al. 2011; Angelova et al. 2012; Dimitrov et al. 2012; Uzunov et al. 2012). Pilot plant operations have also been tested (Vlaev et al. 2011).

As far as the authors are aware, the highest capacity of oil sorption reported thus far for rice husks has been in a study which first pretreated and subsequently prepared the rice husks via thermal treatment under CO_2 (200 ml/min flow) at 300–800 °C for 1 h (Kenes et al. 2012). It was observed that the density of the sorbate had a direct effect on the sorption capacity. The lowest density hydrocarbon (gasoline $\rho = 0.734$ g/cm^3) showed a sorption capacity of 4.5 g/g whereas the highest density hydrocarbon (heavy crude petroleum $\rho = 0.937$ g/cm^3) showed a sorption capacity of 15 g/g (Kenes et al. 2012). Herein, we have used a simple method for the production of oil sorbent materials with uptake capacities higher than any previously reported in literature for rice husk-derived absorbents.

Materials and methods

The rice husks (also referred to as rice hulls) were harvested and collected in Mainland China. They were

Table 1 Specifications of marine fuel RMG380 as specified by ISO 8217: petroleum products–fuels (class F)

Parameter	Unit	Limit	RMG 380
Viscosity at 50 °C	mm^2/s	Max	380
Density at 15 °C	kg/m^3	Max	991
Water	% V/V	Max	0.5
Pour point (upper), summer	°C	Max	30
Pour point (upper), winter	°C	Max	30
Flash point	°C	Min	60

kindly donated to the research team by a Hong Kong based company (Peako Biomass Energy Ltd.). The husks are golden brown in color and averagely <1 cm in length. Residual (marine) diesel was used as the petroleum product to test the rice husk sorption capacities. The marine diesel was obtained from Gulf Oil Marine Ltd. (X 1L—M380, RMG ISO 8217). The nominal specifications of the fuel provided by the supplier can be seen in Table 1.

As can be seen from Table 1 the density of the fuel is indicated to be a maximum value of 991 kg/m^3 at 15 °C. Since the experiments were carried out at room temperature (22–25 °C) it is expected for the marine diesel to be slightly less dense. However, it should also be noted that with time the volatile fraction of the marine diesel will evaporate leaving behind a thicker liquid.

The husks were first sieved by a stainless steel net to remove any powder or broken pieces of hull. All remaining pieces were fully in-tact hulls. The sieved husks were dried and kept at 90 °C in the oven. In each experimental run, husks were treated with various molarities of NaOH solution. After the reaction duration was fulfilled the husk was left to cool to room temperature, filtered, washed, dried and collected.

For the sorption tests 0.2 g of the alkali treated husk was sieved, weighed, and submerged into the marine diesel. The sieving process is carried out so that no powder product will fall through the net during the experiment and contaminate the marine diesel bath. Unless otherwise specified, the sieve is left submerged in the oil for 30 min before it is removed and left to drain. The weight of the wet net and sorbent are measured after 15 min of drainage. The amount of RMG380 taken by the empty net (without any husk) is measured in a separate blank run. The final oil sorption capacity of the rice husk is calculated after the weight of the marine diesel uptaken by the net and the weight of the dry husk are deducted from the final measured weight with Eq. 1:

$$C = \frac{M_{total} - M_{empty} - M_{husk}}{M_{husk}} \tag{1}$$

where C is the sorption capacity of the as-prepared husk [gRMG380/gsorbent], M_{total} is the total weight of the experimental apparatus, M_{empty} is the weight of the liquid taken by the net, and M_{husk} is the weight of the dry sorbent used.

The FTIR spectra were obtained for a wave number range of 4,000–400 cm^{-1} on a Nicolet 550 Magna-IR spectrometer (Nicolet Instrument Corp., Madison, WI) equipped with OMNIC software. The experiments were repeated several times and the results were normalized after acquisition for comparative purposes. The specific surface area of the materials was characterized by adsorption–desorption of N_2 (Brunauer-Emmett-Teller method, BET) at the temperature of liquid nitrogen (77 K) using an Autosorb1-Quantachrome instrument. The gas used for the analysis was 99.9 % pure.

Results and discussion

Compared with other technologies, alkali treatment processes utilize lower temperatures and pressures because they can be carried out at ambient conditions. However, the times required for alkali treatment are much longer than some other technologies which may require only minutes. When compared with acid treatments, alkali treatments lead to less sugar degradation. Sodium hydroxide is the most widely studied caustic material for lignocellulose treatment (Kumar et al. 2009).

In the current research rice husk samples were treated with alkali followed by subsequent testing of their diesel sorption abilities. Although hundreds of articles have targeted oil sorption with various sorbents, as far as the authors are aware there is no account in the literature of employing this simple yet effective method for preparing oil sorption materials from rice husks. After the oil is uptaken by the as-prepared husks it can either be recovered (Asadpour et al. 2013; Wang et al. 2013), or, the oil–rich rice husk sorbent could be directly used as a

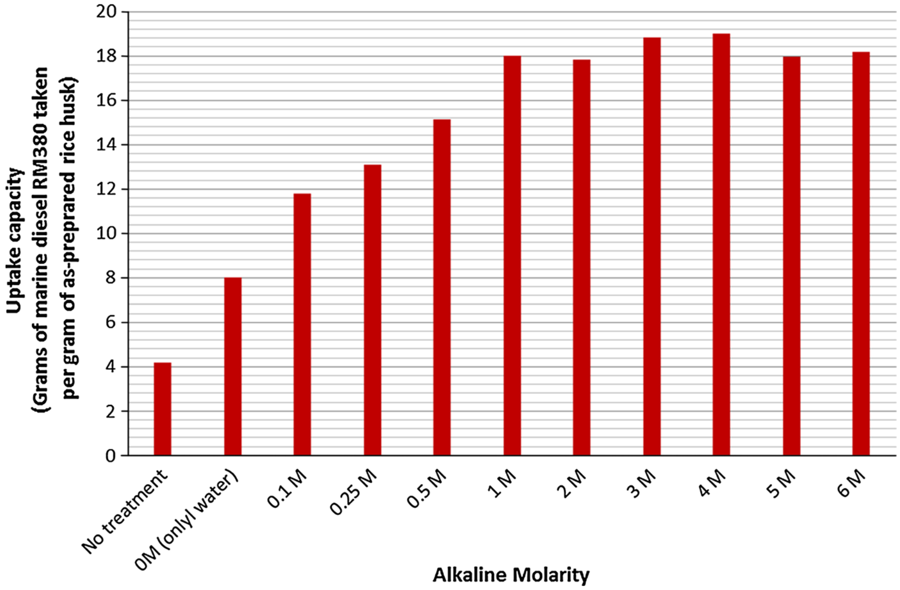


Fig. 1 RMG380 Marine diesel uptake versus the concentration of the NaOH used in the treatment process

solid fuel with high calorific value (Karakasi and Moutsatsou 2013). Another added benefit of alkali treatment is the possibility to leach and chemically remove the silica content from the biowaste in the form of sodium silicate. The soluble sodium silicate could in turn be precipitated and used as a raw material for the production of silica gel and other valuable products.

Effect of NaOH concentration

The alkali concentrations tested to treat the husks at 90 °C were 0.1, 0.25, 0.5, 1, 2, 3, and 6 M. One sample was also treaty only with hot water and denoted as 0 M. Raw rice husks without any treatment were used as control samples. The marine diesel uptake values can be seen in Fig. 1. Observably even treatment with hot deionized water increases the oil uptake of the rice husk. This is thought to be because of the removal of water-soluble impurities. Nearly 15 % weight of the sample is removed with water-treatment which results in brisk brown (less golden) husks. The solid yield of the treated husks is seen to decrease as the caustic concentration increases. The sizable effect of alkali treatment on the yield can be best seen from the 0.1 M sample. Even the mild 0.1 M NaOH treatment results in more than 50 % weight reduction. This is because even mild concentrations of NaOH can remove natural fat and wax on the husk surface as well as some other components such as hemicellulose (Ndazi et al. 2007a, b). Oil uptakes of samples in the range of 2–6 M NaOH treatment give more or less the same results. Higher concentrations than 2M do not decrease the yield considerably. This is thought to be due to removal of all alkali soluble materials. As the molarity of the alkali is increased, the macroscopic and physical state of the husk becomes more broken down resembling mercerization.

Effect of reaction time

As seen in Fig. 2, RMG380 marine diesel sorption capacity increases with the increase of reaction duration. However, after about 12 h of reaction further continuation does not increase marine diesel uptake. This can be explained as follows: with the increase of time, the alkali solution has more opportunity to break-down the husk structure. Since lignin is known to be what gives cellulosic materials their rigidity, the loss of lignin results in smaller and fluffier fibrous fragments. When sufficient time has passed, all alkali soluble components are removed and so the remaining treatment is ineffective in making the structure of the as-prepared material any more suitable for RMG380 uptake. Evidently there is an inverse relationship between the yield and marine diesel uptake. This is

Fig. 2 The effect of reaction time on RMG380 uptake capacity

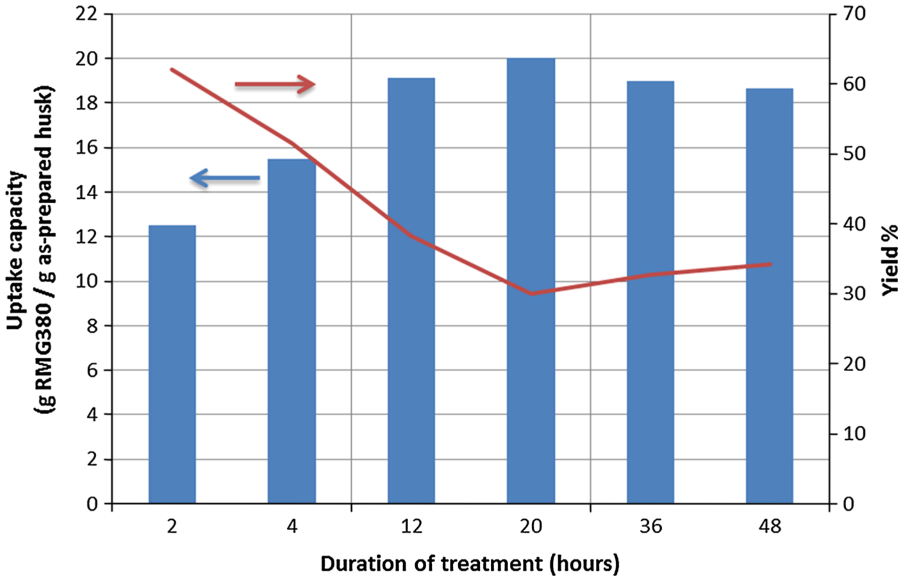
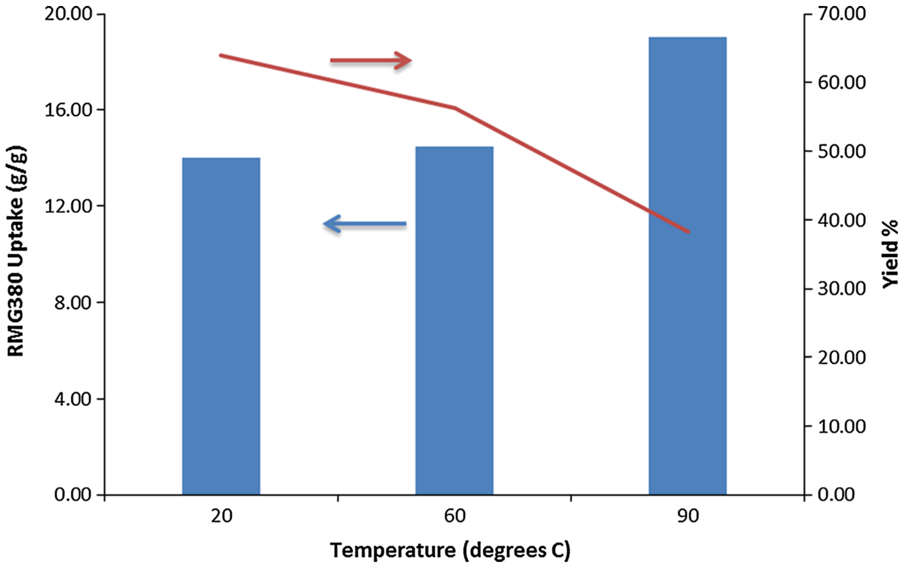


Fig. 3 The effect of treatment temperature on yield and RMG380 uptake. The samples have been treated with 1 M NaOH solution for 12 h. Solid loading is 16 g/l



because lower yields result in more macroscopic void spaces for retaining the liquid.

Effect of reaction temperature

Figure 3 shows the effect of treatment temperature on the marine diesel uptake. Evidently, the higher the temperature is, the more efficient the break-down of the husk will be. More extensive break-down (and hence lower yields) result in a lower bulk density and higher liquid uptake.

Overall analysis

Endwise degradation or peeling of cellulose can occur in alkali media. This reaction is also called endwise depolymerization. Reports have shown that the final product still contains noticeable amounts of reducing endgroups (Li et al. 2007). This is ascribed to the fact that the degradation has reached a crystalline region which is inaccessible to alkali and hence stopped. The alkali concentration affects both the physical accessibility and the relative rates of peeling and stopping reactions. It is speculated that the degradation first increases due to higher accessibility, and is impeded due to the formation of stable endgroups at higher alkalinity. The hydrogen bond of cellulose is disrupted as a result of alkali treatment and thereby the surface roughness of the samples increases. Also, wax and oils covering the external parts of the fiber cell wall are removed. So alkali treatment increases both the surface roughness resulting in better mechanical interlocking, and the amount of cellulose exposed on the fiber surface (increasing the number of possible reaction sites) (Li et al. 2007).

Various constituents of the lignocellulosic materials are cemented together by lignin. The integrity, structural rigidity, and resistance towards swelling are due to the presence of lignin. Compared to most other biowastes rice hulls have high lignin content. Logically the delignification processes can improve the rate and extent of rice husk break-down. Lignin type, content, and distribution are of importance. The reason for improved rate of hydrolysis by removal of lignin might be related to a better surface accessibility (Taherzadeh and Karimi 2008). Since C–C bonds are usually very resistive to chemical attack the degradation or fragmentation of lignin is largely limited to breakage of ether units. Similar to cellulose and hemicellulose, lignin has a tendency to form hydrogen bonds. Both lignin and cellulose form strong hydrogen bonds when dried and therefore their subsequent adsorption of water is diminished (Lai 1996).

In rice husks, alkali treatment has shown to break the cell wall by dissolving hemicellulose, lignin, and silica; by hydrolyzing uronic and acetic acid esters; and by swelling cellulose. The degree to which each of the constituents dissolves depends on various parameters such as alkali concentration and temperature (Juliano 1985). The treated rice husk exhibits a decreased bulk density which allows more oil to seep inside the sorbent. The majority of the absorbed oil is not directly in contact with the walls of the solid, but rather is retained due to cohesion, surface tension, and capillary forces. It is important to keep in mind that the uptake capacity observed is mainly a function of bulk absorption, and not surface adsorption. Hence the internal BET surface area will not have a considerable effect on the sorption capacities. In order to show the effect of various parameters, the relevant information of three representative samples has been compared in Table 2. The three samples are raw rice hulls, those which have undergone mild alkali treatment, and those which have been treated with concentrated alkali.

Table 2 Comparison of alkali treatment effects

	No treatment	Weak alkali treatment	Strong alkali treatment
Yield (%)	100	42.8	35
BET surface area (m^2/g)	2.3	2.6	3.5
Bulk density (kg/m^3)	82	62	35
Highest measured uptake capacity (g RMG380/g as-prepared husk)	4.5	17.5	20.1

Evidently, even concentrated alkali treatment has no considerable effect on the BET surface area of the sample. Hence the macroscopic feature of the samples (i.e. the bulk density) appears to be the main factor regarding marine diesel uptake. Contact angle measurements (not shown here) also revealed that the hydrophobicity of the surface is not beneficially altered due to the treatment. This is because the waxes and other hydrophobic materials have been removed and the as-prepared sample is comprised of mainly hydrophilic cellulose.

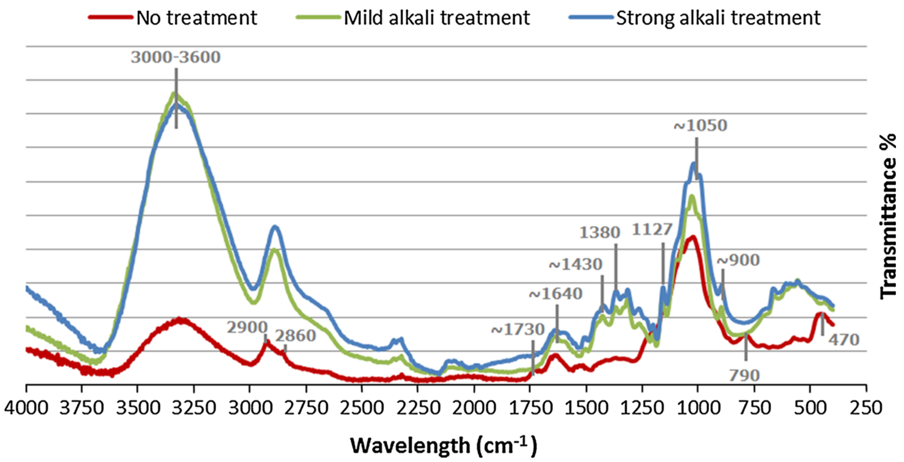
To further investigate the claim of the importance of bulk density, the sample treated with strong alkali was compressed followed by subsequent testing of the uptake capacity. Table 3 clearly shows that the physical compression of the sample considerably reduces the uptake capacity. The compressed samples lost their fluffy structure and turned into flat sheets which remained flat even after 5 months.

The surface functional groups of the alkali treated samples were also further analyzed with FTIR spectra

Table 3 The effect of physical compression on RMG380 uptake capacity

	Average measured RMG380 uptake capacity (g/g)	Highest measured RMG380 uptake capacity (g/g)
Strong alkali treated sample	19.5	20.1
Compressed strong alkali treated sample (500 bar for 10 s)	10.3	11

Fig. 4 FTIR Spectra of treated and untreated rice husk



analysis. Figure 4 compares the FTIR results of the untreated, mildly alkali treated, and strongly alkali treated husks.

The large peak at 3,000–3,600 cm^{-1} is representative of strong hydrogen bonding due to hydroxyl (OH) groups of the cellulose. The absorbance ratio of the bands at about 1,430 and 900 cm^{-1} is referred to as the crystallinity index. The larger band denotes the crystalline absorption, while the smaller shows the amorphous part. The more broad these peaks are, the more disordered the structure of the cellulose is. One might conclude that the results show that by alkali treatment, the crystallinity of the rice husk samples increases. However, this is in contrast with general knowledge regarding the mercerization of pure cellulose which is known to decrease the crystallinity index. Also, since the absorbance at approximately 900 cm^{-1} is shown to increase as cellulose I transforms into cellulose II, we can conclude that this transformation has not occurred prevalently here (Oh et al. 2005). Further scrutiny of XRD patterns (not shown here) affirms the fact that no conversion to cellulose II has occurred (French 2013). The overlapping band at 1,050 cm^{-1} has also been ascribed to Si–O stretching (He et al. 2013). Hence the untreated rice husk which contains a high silica content shows a high intensity at this wavelength. After alkali treatment, the silica is removed in the form of sodium silicate, and therefore the relative intensity of this band decreases.

The small peak at around 1,640 cm^{-1} corresponds to the absorption of water. Some hemicellulose and lignin material have clearly been removed. For example, the shoulder observed at around 1,730 cm^{-1} seen in the raw rice husk is no more present after the treatment. This is ascribed to the removal of acetyl and ester groups in hemicellulose or carboxylic acid groups in the lignin (Johar et al. 2012). The bands at 1,473 and 1,380 cm^{-1} show the C–H symmetric and asymmetric deformations, respectively (Sun et al. 2005). Similarly, the bands at 2,900 and 2,860 correspond to asymmetric and symmetric stretching vibrations of the aliphatic C–H bonds in $-CH_3$ and $-CH_2$ groups in the structures of cellulose, hemicellulose, and lignin, respectively (He et al. 2013). The bands at approximately 470 and 790 cm^{-1} which exist in the raw husk but are removed with the alkali treatment can be associated with Si–H bonds (Nakbanpote et al. 2007). The band at 1,127 cm^{-1} could be indicative of C–O stretching in Na^{+}–lignosulfonics (Shen et al. 2008).

Further studies could be carried out to make use of the silicon which is leached during the alkali treatment process in the form of sodium silicate. The silicon can be recovered in the form of a silica gel by reducing the PH (Foletto et al. 2006). Initial experiments have been done and suitable results have been obtained. Porous silica with BET surface areas exceeding 200 m^2/g and good purity has been recovered. Various reviews and studies regarding the recovery of porous silica from rice are available in the literature (Sun and Gong 2001; Chandrasekhar et al. 2003). Hence another benefit of the current proposed process is the production of two products at the same time: the first being an oil absorbent, the other a siliceous product. Considering the total silica content within various batches of rice husks, the total amount of soluble silica (in the form of sodium silicate) would be 10–20 % weight of the raw rice husk. Considering the fact that about 20 kg of husk are produced per 100 kg of rice paddy product, this would amount to 2–4 kg of soluble silica per 100 kg of rice grain produced. Alongside other value-added applications (Santamaría et al. 2013; Shao et al. 2013; Kim et al. 2013), the sodium silicate could also be used for catalytic purposes for biodiesel and fatty acid production (Fan et al. 2013; Long et al. 2014).

Conclusion

Rice husks have been used as feedstock for the production of oil sorbent materials. Simple, safe, and cheap alkali treatment was shown to break-down the rice husk structure and produce as-prepared products with satisfactory oil uptake capacities. The proposed method uses low temperatures and results in high product yields. BET and FTIR analysis have shown that micro- and nano-porosity as well as surface functional groups are not determining factors in the superior uptake capacities. The marine diesel sorption capacity is shown to have a strong inverse relation with the bulk density.

Acknowledgments The authors would like to sincerely thank the staff at the MCPF and AEMF departments at the Hong Kong University and Technology, as well as Mr. Ronnie Lo of Peako Biomass Energy Co. for their assistance.

References

Adebajo MO, Frost RL, Kloprogge JT et al (2003) Porous materials for oil spill cleanup: a review of synthesis and absorbing properties. J Porous Mater 10:159–170. doi:10.1023/A:1027484117065

Angelova D, Uzunov I, Uzunova S et al (2011) Kinetics of oil and oil products adsorption by carbonized rice husks. Chem Eng J 172:306–311. doi:10.1016/j.cej.2011.05.114

Angelova D, Uzunova S, Uzunov I, Anchev B (2012) Dependence between oil sorption capacity of pyrolyzed rice husks and the composition and amount of fluids dispersed on their surface. J Univ Chem Technol Metall 47:147–154

Asadpour R, Sapari NB, Tuan ZZ et al (2013) Application of sorbent materials in oil spill management: a review. Casp J Appl Sci Res 2:46–58

Asfad MN, Darabinia M (2013) Performance of Kuwait regional convention on Persian Gulf marine environment. J Maz Univ Med Sci 22:71–78

Chandrasekhar S, Satyanarayana KG, Pramada PN et al (2003) Review processing, properties and applications of reactive silica from rice husk—an overview. J Mater Sci 38:3159–3168. doi:10.1023/A:1025157114800

Deymeh H, Shadizadeh SR, Motafakkerfard R (2012) Experimental investigation of *Seidlitzia rosmarinus* effect on oil–water interfacial tension: usable for chemical enhanced oil recovery. Sci Iran 19:1661–1664. doi:10.1016/j.scient.2012.04.020

Dimitrov A, Genieva S, Petkov P, Vlaev L (2012) Using pyrolyzed rice husks as an adsorbent for purification of water basins polluted with diesel fuel. Water Air Soil Pollut 223:5087–5095. doi:10.1007/s11270-012-1260-z

El-Fadel M, Abdallah R, Rachid G (2012) A modeling approach toward oil spill management along the Eastern Mediterranean. J Environ Manage 113:93–102. doi:10.1016/j.jenvman.2012.07.035

Elhakeem AA, Elshorbagy W, Chebbi R (2007) Oil spill simulation and validation in the Arabian (Persian) Gulf with special reference to the UAE coast. Water Air Soil Pollut 184:243–254

Fan F, Jia L, Guo X et al (2013) Preparation of novel ethylene glycol monomethyl ether fatty acid monoester biodiesel using calcined sodium silicate. Energy Fuels 27:5215–5221. doi:10.1021/ef401514e

FAOSTAT (2013a) Food and agriculture organization of the United Nations statistics. http://faostat.fao.org/site/339/default.aspx

FAOSTAT (2013b) Food and agriculture organization of the United Nations statistics—new website. http://faostat3.fao.org/home/index.html#VISUALIZE

Foletto EL, Gratieri E, de Oliveira LH, Jahn SL (2006) Conversion of rice hull ash into soluble sodium silicate. Mater Res 9:335–338

French AD (2013) Idealized powder diffraction patterns for cellulose polymorphs. Cellulose 1–12. doi:10.1007/s10570-013-0030-4

He D, Ikeda-Ohno A, Boland DD, Waite TD (2013) Synthesis and characterization of antibacterial silver nanoparticle-impregnated rice husks and rice husk ash. Environ Sci Technol 47:5276–5284. doi:10.1021/es303890y

Hirotsu N, Kashiwagi T, Madoka Y, Ishimaru K (2007) Strategies to improve plant height for the production of biomass energy in rice. Jpn J Crop Sci 76:501–507

Hongo T, Sugiyama J, Yamazaki A, Yamasaki A (2013) Synthesis of aluminosilicate nanotube from rice husk ash and its characterization. Nanopages 8:9–14. doi:10.1556/Nano.00003

Johar N, Ahmad I, Dufresne A (2012) Extraction, preparation and characterization of cellulose fibres and nanocrystals from rice husk. Ind Crops Prod 37:93–99. doi:10.1016/j.indcrop.2011.12.016

Juliano BO (1985) Rice hull and rice straw. In: Juliano BO (ed) Rice chemistry and technology, 2nd edn. American Association of Cereal Chemists, Minnesota, pp 689–755

Kamoshita A (2007) Historical changes in urban rice production systems in Tokyo, Japan. Plant Prod Sci 10:245–269

Kamsonlian S, Suresh S, Ramanaiah V et al (2012) Biosorptive behaviour of mango leaf powder and rice husk for arsenic(III) from aqueous solutions. Int J Environ Sci Technol 9:565–578. doi:10.1007/s13762-012-0054-6

Karakasi OK, Moutsatsou A (2013) By-products: oil sorbents as a potential energy source. Waste Manag Res 31:376–383

Kenes K, Yerdos O, Zulkhair M, Yerlan D (2012) Study on the effectiveness of thermally treated rice husks for petroleum adsorption. J Non Cryst Solids 358:2964–2969. doi:10.1016/j.jnoncrysol.2012.07.017

Khush GS (2005) What it will take to Feed 5.0 Billion Rice consumers in 2030. Plant Mol Biol 59:1–6

Kim YK, Rajesh KP, Yu J-S (2013) Zeolite materials prepared using silicate waste from template synthesis of ordered mesoporous carbon. J Hazard Mater 260:350–357. doi:10.1016/j.jhazmat.2013.05.009

Kirby MF, Law RJ (2008) Oil spill treatment products approval: the UK approach and potential application to the Gulf region. Mar Pollut Bull 56:1243–1247. doi:10.1016/j.marpolbul.2008.03.002

Kumagai S, Noguchi Y, Kurimoto Y, Takeda K (2007) Oil adsorbent produced by the carbonization of rice husks. Waste Manag 27:554–561. doi:10.1016/j.wasman.2006.04.006

Kumar P, Barrett DM, Delwiche MJ, Stroeve P (2009) Methods for pretreatment of lignocellulosic biomass for efficient hydrolysis and biofuel production. Ind Eng Chem Res 48:3713–3729. doi:10.1021/ie801542g

Lai Y-Z (1996) Reactivity and accessibility of cellulose, hemicelluloses, and lignins. In: Hon DN-S (ed) Chem. Modif. Lignocellul. Mater. Marcel Dekker, New York, pp 35–95

Li X, Tabil LG, Panigrahi S (2007) Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review. J Polym Environ 15:25–33. doi:10.1007/s10924-006-0042-3

Long Y-D, Fang Z, Su T-C, Yang Q (2014) Co-production of biodiesel and hydrogen from rapeseed and Jatropha oils with sodium silicate and Ni catalysts. Appl Energy 113:1819–1825. doi:10.1016/j.apenergy.2012.12.076

Lordan J, Pascual M, Fonseca F et al (2013) Use of rice husk to enhance peach tree performance in soils with limiting physical properties. Soil Tillage Res 129:19–22. doi:10.1016/j.still.2013.01.002

Malekmohammadi I, Hosseini SJF, Yazdani S, Shadfar S (2011) Analytical globalized state intervention model in rice production development. African J Agric Res 6:2015–2025

Mehdinia SM, Latif PA, Taghipour H (2013) A comparative evaluation of dried activated sludge and mixed dried activated sludge with rice husk silica to remove hydrogen sulfide. Iran J Environ Heal Sci Eng 10:22

Naing TAA, Kingsbury AJ, Buerkert A, Finckh MR (2008) A survey of Myanmar rice production and constraints. J Agric Rural Dev Trop Subtrop 109:151–168

Nakbanpote W, Goodman BA, Thiravetyan P (2007) Copper adsorption on rice husk derived materials studied by EPR and FTIR. Coll Surf A Physicochem Eng Asp 304:7–13. doi:10.1016/j.colsurfa.2007.04.013

Ndazi BS, Karlsson S, Tesha JV, Nyahumwa CW (2007a) Chemical and physical modifications of rice husks for use as composite panels. Compos Part A Appl Sci Manuf 38:925–935. doi:10.1016/j.compositesa.2006.07.004

Ndazi BSN, Nyahumwa CW, Tesha J (2007b) Chemical and thermal stability of rice husks against alkali treatment. BioResources 3:1267–1277

Nwankwere ET, Emmanuel GC, Adagadzu KJ, Yusuf NB (2010) Sorption studies of crude oil on acetylated rice husks. Arch Appl Sci Res 2:142–151

Oh SY, Yoo D, Shin Y II, Seo G (2005) FTIR analysis of cellulose treated with sodium hydroxide and carbon dioxide. Carbohydr Res 340:417–428. doi:10.1016/j.carres.2004.11.027

Peng S, Tang Q, Zou Y (2009) Current status and challenges of rice production in China. Plant Prod Sci 12:3–8

Pereira CL, Savastano H Jr, Payá J et al (2013) Use of highly reactive rice husk ash in the production of cement matrix reinforced with green coconut fiber. Ind Crops Prod 49:88–96. doi:10.1016/j.indcrop.2013.04.038

Peter Rosner L, McCulloch N (2008) A note on rice production, consumption, and import data in Indonesia. Bull Indones Econ Stud 44:81–92. doi:10.1080/00074910802001595

Rajakovic V, Aleksic G, Radetic M, Rajakovic L (2007) Efficiency of oil removal from real wastewater with different sorbent materials. J Hazard Mater 143:494–499. doi:10.1016/j.jhazmat.2006.09.060

Rajaković-Ognjanović V, Aleksić G, Rajaković L (2008) Governing factors for motor oil removal from water with different sorption materials. J Hazard Mater 154:558–563. doi:10.1016/j.jhazmat.2007.10.066

Safa Y, Bhatti HN (2011a) Adsorptive removal of direct textile dyes by low cost agricultural waste: Application of factorial design analysis. Chem Eng J 167:35–41. doi:10.1016/j.cej.2010.11.103

Safa Y, Bhatti HN (2011b) Kinetic and thermodynamic modeling for the removal of Direct Red-31 and Direct Orange-26 dyes from aqueous solutions by rice husk. Desalination 272:313–322. doi:10.1016/j.desal.2011.01.040

Santamaría E, Maestro A, Porras M et al (2013) A novel approach to the industrial preparation of mesostructured silica: use of ion exchange resin and study of the effect of composition variables. Chem Eng J 226:7–12. doi:10.1016/j.cej.2013.04.025

Sayed SA, Zayed AM (2006) Investigation of the effectiveness of some adsorbent materials in oil spill clean-ups. Desalination 194:90–100. doi:10.1016/j.desal.2005.10.027

Seyedi SM, Rajaei S, Raiesi F et al (2013) Characterization and potentials of indigenous oil-degrading bacteria inhabiting the rhizosphere of wild oat (*Avena fatua* L.) in south west of Iran. Iran J Biotechnol 11:32–40

Shao Z, Luo F, Cheng X, Zhang Y (2013) Superhydrophobic sodium silicate based silica aerogel prepared by ambient pressure drying. Mater Chem Phys 141:570–575. doi:10.1016/j.matchemphys.2013.05.064

Shen Q, Zhang T, Zhu M-F (2008) A comparison of the surface properties of lignin and sulfonated lignins by FTIR spectroscopy and wicking technique. Coll Surf A Physicochem Eng Asp 320:57–60. doi:10.1016/j.colsurfa.2008.01.012

Stoop WA, Adam A, Kassam A (2009) Comparing rice production systems: a challenge for agronomic research and for the dissemination of knowledge-intensive farming practices. Agric Water Manag 96:1491–1501. doi:10.1016/j.agwat.2009.06.022

Sun L, Gong K (2001) Silicon-based materials from rice husks and their applications. Ind Eng Chem Res 40:5861–5877. doi:10.1021/ie010284b

Sun XF, Xu F, Sun RC et al (2005) Characteristics of degraded cellulose obtained from steam-exploded wheat straw.

Carbohydr Res 340:97–106. doi:10.1016/j.carres.2004.10.022

Suni S, Kosunen A-L, Hautala M et al (2004) Use of a by-product of peat excavation, cotton grass fibre, as a sorbent for oil-spills. Mar Pollut Bull 49:916–921. doi:10.1016/j.marpolbul.2004.06.015

Sweeney M, McCouch S (2007) The complex history of the domestication of rice. Ann Bot 100:951–957

Taherzadeh MJ, Karimi K (2008) Pretreatment of lignocellulosic wastes to improve ethanol and biogas production: a review. Int J Mol Sci 9:1621–1651. doi:10.3390/ijms9091621

Talpur MA, Changying J, Junejo SA et al (2011) A review on the enhancement of rice production in paddy field with minimum input of water. African J Agric Res 6:6776–6779

United Nations Group of Experts on Geographical Names (2006) Historical, geographical and legal validity of the Name: PERSIAN GULF. United Nations, Vienna

Uzunov I, Uzunova S, Angelova D, Gigova A (2012) Effects of the pyrolysis process on the oil sorption capacity of rice husk. J Anal Appl Pyrolysis 98:166–176. doi:10.1016/j.jaap.2012.07.007

Van Nguyen N, Ferrero A (2006) Meeting the challenges of global rice production. Paddy Water Environ 4:1–9

Verma P, Wate S, Devotta S (2008) Simulation of impact of oil spill in the ocean—a case study of Arabian Gulf. Environ Monit Assess 146:191–201. doi:10.1007/s10661-007-0071-y

Vlaev L, Petkov P, Dimitrov A, Genieva S (2011) Cleanup of water polluted with crude oil or diesel fuel using rice husks ash. J Taiwan Inst Chem Eng 42:957–964. doi:10.1016/j.jtice.2011.04.004

Wahi R, Chuah LA, Choong TSY et al (2013) Oil removal from aqueous state by natural fibrous sorbent: an overview. Sep Purif Technol 113:51–63. doi:10.1016/j.seppur.2013.04.015

Wang B, Karthikeyan R, Lu X-Y, et al (2013) Hollow carbon fibers derived from natural cotton as effective sorbents for oil spill cleanup. Ind Eng Chem Res. doi:10.1021/ie402371n