



Since 1969



A Physical Coal Cleaning Approach for Clean Energy Production from Low Grade Lakhra Coal of Pakistan Using Diester Table

M. Asif¹, M.A. Hussain², A. Riaz³, R. Mujahid³, M.S. Akram⁴, B. Haider⁵, S. Kanwal^{6*}, H. Zeb^{6*},
R.E. Haq⁴, M. Taveer⁴

Submitted: 14/04/2023, Accepted: 16/08/2023, Online: 07/09/2023

Abstract

In this work coal from Lakhra (coal mine in Pakistan) was subjected to a physical technique for mineral matter and sulfur reduction by using diester table. Effect of particle size and coal-to-water ratio of slurry were studied. A reduction of 85% in sulfur content and 88% in ash content for 500 μm coal sample was observed. While at 300 μm size sulfur and ash content were reduced about 77% and 80% respectively. At 150 μm size, the reduction in sulfur and ash was observed to be lesser (54% and 55% respectively) due to the decrease in specific gravity difference of coal and impurity (i.e. sulfur and ash). GCV increased from 17.2 MJ/kg of the raw coal to 23.3 MJ/kg of cleaner fraction obtained at 500 μm . Based on the results of this study, diester table can be proposed to be a simpler however an effective physical coal cleaning method to reduce sulfur and ash content. Besides other parameters, particle size is a crucial parameter to impact the cleaning efficiency and because of the greater difference in specific gravity of coal and impurity, higher particles size used in this study resulted in the cleanest product.

Keywords: Clean Energy Production, Diester Table, Physical Coal Cleaning, Specific Gravity

1. Introduction:

Coal has a long and rich history of use in providing a source of energy and electricity. Coal is considered as one of the major sources of energy and electricity generation, meeting approximately 25% of the world's primary energy and 40% of the global electricity demand [1,2]. Among different motives of its increased global utilization, its

abundance, affordability, and versatility are the most significant ones. According to British Petroleum (BP) Statistical Review of World Energy 2019 the total proven coal reserves of the world are about 1.114 trillion tons (equivalent to $220 - 280 \times 10^{21} \text{ J}$), which have larger energy potential than the combined resource of oil and gas[3].

Coal is a combustible organic sedimentary rock of a

¹School of Mechanical Engineering, Sungkyunkwan University, 2066, Seobu-Ro, Jangan-Gu, Suwon, Gyeong Gi-Do 16419, South Korea.

²Institute of Metallurgy & Materials Engineering, University of the Punjab, Pakistan.

³Department of Chemical Engineering, Khwaja Fareed University of Engineering & Information Technology, Rahim Yar Khan.

⁴Institute of Energy and Environmental Engineering, University of the Punjab, Pakistan.

⁵Institute of Chemical Engineering and Technology, University of the Punjab, Pakistan.

⁶Department of Environmental Sciences, University of Narowal.

*Correspondence Author: sumaira.kanwal@uon.edu.pk, hassanzeb.ieee@pu.edu.pk

plant origin which is formed by dumping of plant in the subsurface of earth after a long geological period under elevated temperature and pressure. But during its formation some unwanted inorganic components are added in it from its surrounding which cause problems during burning of coal in a power station [4]. Coal has five major organic elements of organic nature; carbon, hydrogen, sulfur, nitrogen and oxygen (CHSNO) and almost 76 trace elements of inorganic material. Among the organics, sulfur and nitrogen are environmentally hazardous elements. During mining, the high sulfur containing low rank coal produces acid mine drainage which affects the soil fertility by dissolving some heavy metals [5]. These dissolved heavy metals eventually get mixed with underground water aquifer polluting it. These nitrogen and sulfur containing species produce their respective oxides (NO_x and SO_x) on combustion which cause many health (cardiovascular diseases, lungs diseases etc.) as well as environmental (acid rain, winter smog, visibility) problems [6]. Acid rain causes many environmental issues including leaching out mineral from soil disturbing soil fertility which hinders growth of plants. It also affects the aquatic life by increasing the acidity of lakes and streams[7].

Coal is also frequently loaded with high inorganic contents (ash content) which are deemed as other constituent contributing to the concerns regarding coal utilization in addition to high sulfur and nitrogen content [8]. Majority of these inorganics consists of silica (50-60%), alumina (25-30%), iron oxide (5-10%), and other alkali and alkaline earth metal oxides are about 5-10% [9]. Problems of high ash content are decreased heating value, particle agglomeration, bed defluidization during combustion of low-ranked coals in fluidized bed boilers, and slagging and fouling behavior causing the decrease in heat transfer efficiency[10][11]. In addition, the presence of sulfur produces SO₂ which is catalyzed by metallic elements of ash and gets converted into SO₃ which further reacts with the moisture of the coal and produces sulfuric acid. The acidic environment causes corrosion in boiler tubes

and decreases their life-time and adds to boiler maintenance cost [12].

Pakistan has a total 185 billion tons coal resources in which about 11.5 billion tons of resources contain high sulfur and ash content. Remaining coal resources consist of lignite coal with high moisture content and low calorific value [13,14]. According to Pakistan energy yearbook 2019, in the Sindh province of Pakistan, a huge reserve of 1.33 billion tons of coking coal at Lakhra district is present containing high sulfur 6.5% and high ash content about 26%. Other reserves of Sindh province (9.95 billion tons) also have high amount of sulfur (5 - 15%) and of ash (16 - 39%) which make it misfit for its safe utilization under environmental restriction. Similarly other high sulfur and high ash content coal reserves in Pakistan include 0.22 billion tons reserves of Baluchistan province with 4 - 10% sulfur and 9 - 34% ash content [15]. According to an environmental protection agency (EPA), sulfur in coal should be less than 0.7% [16]. Hence the utilization of coal resources has been limited by the presence of high level of ash and sulfur in its major deposits.

Amid world energy crisis, the rising price of crude oil and natural gas, and gradual depletion of high-quality coal reserves of the world, there is a dire need of demineralization and desulfurization of low-grade coals to obtain environmentally acceptable clean fuels. To achieve desulfurization and demineralization, both physical methods and the chemical methods are in use. Chemical methods involve the utilization of costly chemical as well as the modification of original coal structure resulting a drop in calorific value. For example, low ranked coals are dissolved in acidic solutions which leads to a decrease in carbon content affecting the calorific value of coal [17]. However, physical methods of coal cleaning (mineral matter and sulfur reduction) are relatively cheap and easy to handle. Current industrial and laboratory physical coal cleaning processes range in complexity from simple systems for removing coarse refuse to highly sophisticated systems designed for maximum removal of sulfur and ash-forming minerals from a coal sample. Physical coal cleaning can be divided into four broad

categories based on the physical properties that are used to affect a separation process; i) specific gravity, ii) surface properties, iii) magnetic susceptibility, and iv) electrical conductivity [18]. Gravity separation depends on the specific gravity difference between coal and its impurities. The specific gravity of clean coal is usually between 1.3 and 1.7 whereas the specific gravity of the mineral matter is between 3.5 and 5.0 [19]. There are many studies for coal cleaning by physical and physicochemical methods like froth flotation [20,21] heavy media separation [22] coal-oil agglomeration [23] but there is hardly any literature available for the cleaning of coal by diester table. This work aims to investigate coal cleaning efficiency of a laboratory diester table in terms of ash and sulfur reduction on Lakhra coal sample. Coal samples of three different sizes (500 μm , 300 μm and 150 μm) were treated with four different coal-to-water ratios (5/95, 10/90, 15/85 and 20/80). The maximum efficiency of coal cleaning is found at 500 μm and at coal-to-water of 20/80 where the reduction in ash is about 88% and reduction in sulfur is about 85%.

2. Material and Methodology:

2.1. Sample Preparation:

A bulk sample of Lakhra coal (40 kg) was obtained from Lakhra coal mine located in Sindh province of Pakistan. Coal lumps were crushed into 4 mm size and kept at 40° C in the oven for the evaporation of surface moisture. It took about 6-8 h to become weight loss constant. The dried sample was crushed and sieved to obtain different particle sizes (including 500 μm , 300 μm , and 150 μm) for experiments. While 250 μm was obtained to carry out the proximate analysis of coal sample. All screened products were separately packed in airtight plastic bags, labelled, and stored for

further use.

2.2 Proximate Analysis:

Moisture was determined according to ASTM D-3173 by placing the sample in an oven at 110 °C for 1h, the volatile matter was determined by using ASTM D-3175 at 950 °C for 7 min and ash content was determined according to ASTM D-3174 at 750 °C for 4-6 h until all black carbon particles disappeared and weight loss became constant. Fixed carbon was calculated by difference method. Gross calorific value was determined by using bomb calorimeter according to ASTM D-5865, and sulfur content was measured by using lab scale Eschka method ASTM D-3177.

2.3 Coal Cleaning by Diester Table:

The 500 μm , 300 μm and 150 μm sizes of coal were treated on diester table. First, 500 μm coal sample (1kg) was used with all four coal-to-water ratios (5/95, 10/90, 15/85 and 20/80). Depending upon the density and size, particles were classified as fines, middling and tailings; and were filtered through a filter paper. After filtration, these fractions were air-dried, and 1g of each fraction was used for each analysis (ash, sulfur and GCV). The same procedures were repeated for 300 μm and 150 μm coal samples.

3. Results and Discussion:

3.1. Proximate Analysis:

Proximate analysis showed significant potential of Lakhra coal to be used in combustion with 55.3 wt% of combustible material (fixed carbon + volatile matter), and GCV of 17.17 MJ/kg as presented in table 1. However, higher sulfur (6.6 wt%) and ash content (24.9 wt%) demands its upgrading to make its utilization environment unfriendly.

Table 1: Proximate composition of Lakhra coal sample

Size	Proximate Analysis (wt %) (ADL)				GCV(MJ/kg)	S wt%
250 μm	Moisture	VM	Ash	FC	17.17	6.6
	19.8	32.3	24.9	23.0		

3.2 Effect of Parameters:

The table is of rectangular shape with some degree of inclination to generate the gradient of flow based on density of particle as shown in Fig 1. Water is used as a mobile phase to keep particle moving from one end of the table to the other. When particles having the same size, but different densities are feed to the table, denser particles are less affected by the water flow and hence they spend more time on the table whereas lighter particles are less

affected by the table shaking and hence spend less time (as flow of water moves them). On the other hand, when particles having same density, but different sizes are introduced to the table, the larger the particle the more it is affected by water flow and vice-versa. It means coarser high-density particles report to the same end of the table as the finer low-density particles which are called the middling product. This emphasizes the importance of pre-sorting of particles with respect to their size for better efficiency of coal cleaning using diester table.

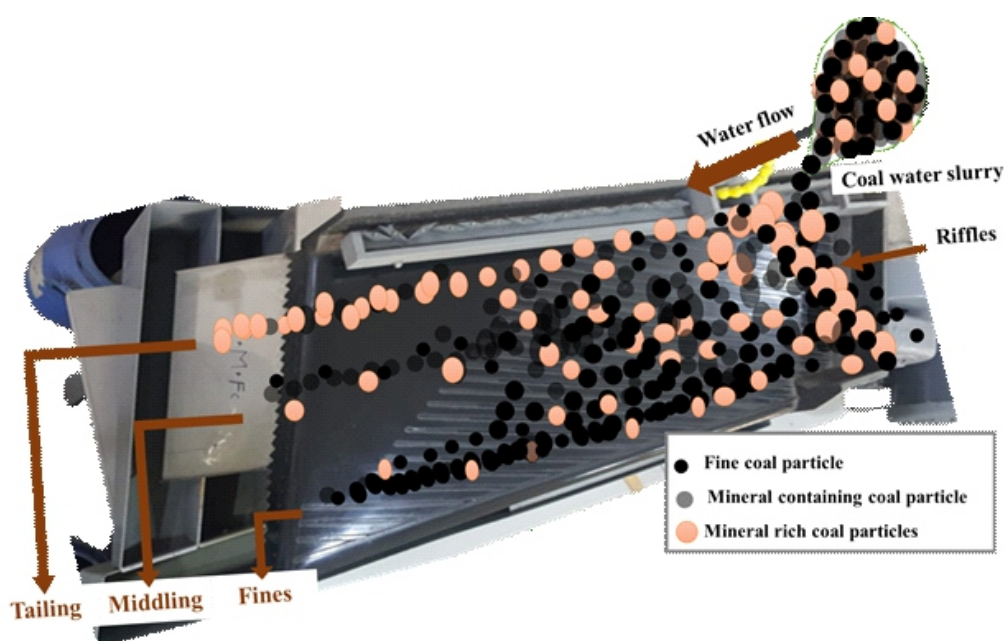


Figure 1: Schematic diagram for highlighting the different parts of diester table

In order to optimize the performance of diester table; a screening study of variables was performed. In this study, variable parameters were coal-to-water ratio and size of coal particles. For this research work, four different coal-to-water ratios and three different coal particle sizes were used. Effect of these two parameters on ash and sulfur reduction have been discussed in detail. Effect of three particles sizes (500 μm , 300 μm , 150 μm) were studied individually for different coal-to-water ratios, as presented in Fig. 2, 3, and 4.

Coal-to-water ratios were altered during the slurry formation step. However, it is worth mentioning that this ratio cannot be strictly monitored at laboratory scale as an uncontrolled amount of water

was continuously added (until all the material on the table was collected) via a water opening for displacing the coal particles towards the edges of diester table

3.3. Reduction in Ash Content:

Theoretically, the best separation efficiency should be obtained for the least concentration of coal particles in water and it should decrease with the increase in concentration [,]. This is because, at increased concentration, there are more chances of separated pyritic particles to recombine with coal organic fraction through agglomeration. The more the water, the more the distance these particles are apart from each other which results in better separation efficiency.

Indeed, the best separation of pyrite and other ash impurities from coal particles was obtained for lesser coal-to-water ratio but it did not follow the trend when the concentration of coal was increased. For example, at 500 μm , ash in the fine and middling first increased from 3wt % (at 5:95 ratio) to 8wt % (at 10:90 ratio) but then started decreasing as coal-to-water ratio was increased to 15:85 (7wt %) and 20:80 (4wt%). In the middling, no trend was observed with the increase in coal-to-water ratio. While at 300 μm and 150 μm , the maximum reduction in ash was observed; about 80 wt% and 54 wt% respectively.

Based on the principle of pyrite and ash separation using diester table, the flow of water on the table affects the lighter particles more than the heavier ones and table shaking affects the heavier particles more. Keeping the particle size fixed (500 μm), fines (which spend lesser time on the table) should be the

cleanest fraction (since it is a lighter fraction) and tailing should be having the most amounts of impurities. Middling is the fraction which is consisted of particles having medium range density particles which means impurities of middling fraction should be in between tailing and fines. Crushing of the feed liberates pyrite and other minerals from coal making its density lower (specific gravity of coal is about 1.5 and that of pyrite is 5). Tailing is the fraction having the maximum amount of ash, fines are the fraction having the least of it, and middling is the fraction having an intermediate amount of ash from all coal-to-water ratios as shown in Fig. 2.

However, for 500 μm size coal particles, the best coal-to-water ratio was proved to be (5:95) hinting towards lesser coal-to-water ratio being beneficial for better efficiency.

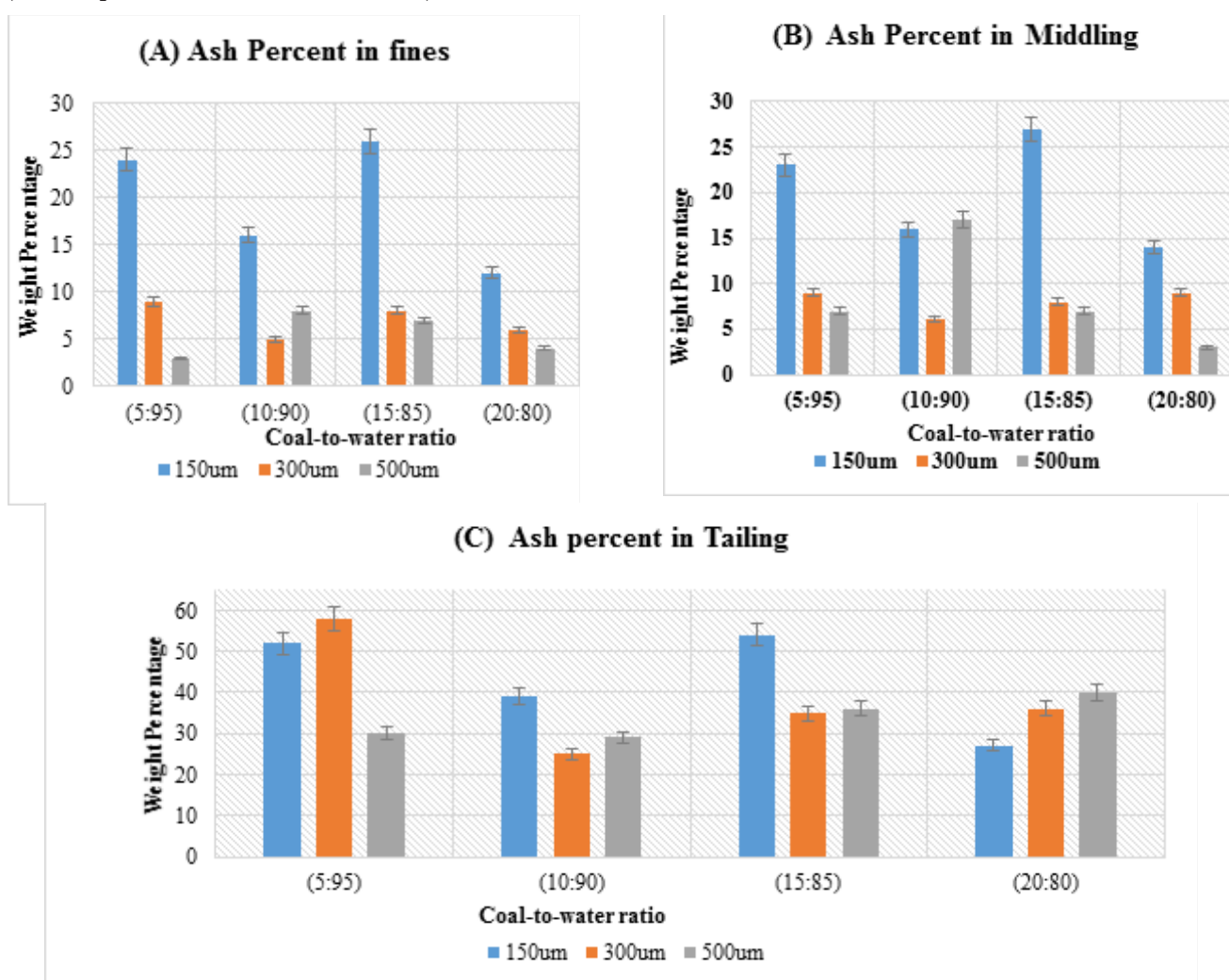


Figure 2: Ash reduction in different fraction after cleaning by diester table

3.4 Reduction in Sulfur Content:

The pyritic sulfur in the fine fraction was lesser at 5:95 (0.95 wt%) as compared to other coal-to-water ratios as depicted by Fig 3. However, in fines, the best separation was obtained for least coal-to-water ratio and maximum amount of pyritic sulfur (87 wt%) was removed as compared to other coal-to-water ratios at 500 μ m size. which is higher efficiency than any other coal cleaning technique including all physical and chemical treatment.

For a fixed coal-to-water ratio of 5:95, fines have the lowest amount of pyritic sulfur, but middling fraction reported to have the highest amount of pyritic sulfur instead of tailing. The exact reason is difficult to sort at the moment, however, the human error involved in the determination of sulfur through the Eschka method could not be ruled out.

Results of 300 μ m coal sample once again showed that there is no clear relationship among the sulfur or ash removing efficiency of diester table with coal-to-water ratio (as explained above). However, for all coal-to-water ratios, fine was the cleanest fraction having the lowest ash and sulfur content. This

showed that diester table can be effectively utilized for the separation of ash and sulfur from coal. 300 μ m coal also has better result for ash and sulfur reduction. Maximum reduction in sulfur was observed with a coal-to-water ratio 10:90 (77% reduction) and similar result was observed at 20:80 ratio while a reduction in ash content of 80% was observed at a coal-to-water ratio 10:90.

So, 150 μ m size showed very poor result for ash and sulfur reduction. Reduction in sulfur and ash was determined to be about 54 wt% and 55 wt% respectively. Very fine size of mineral matter causes the decrease in density difference, so the separation is inefficient. Similarly, when the coal particle size is very large, separation will be difficult too because liberation of mineral matter from coal particle was not properly achieved which is a prerequisite for mineral matter separation. But 500 μ m coal (used in this study) shows better separation of mineral matter as this size seems just large enough to maintain the density difference between inorganic mineral matter and organic coal particle; and small enough to liberate mineral matter from coal particles.

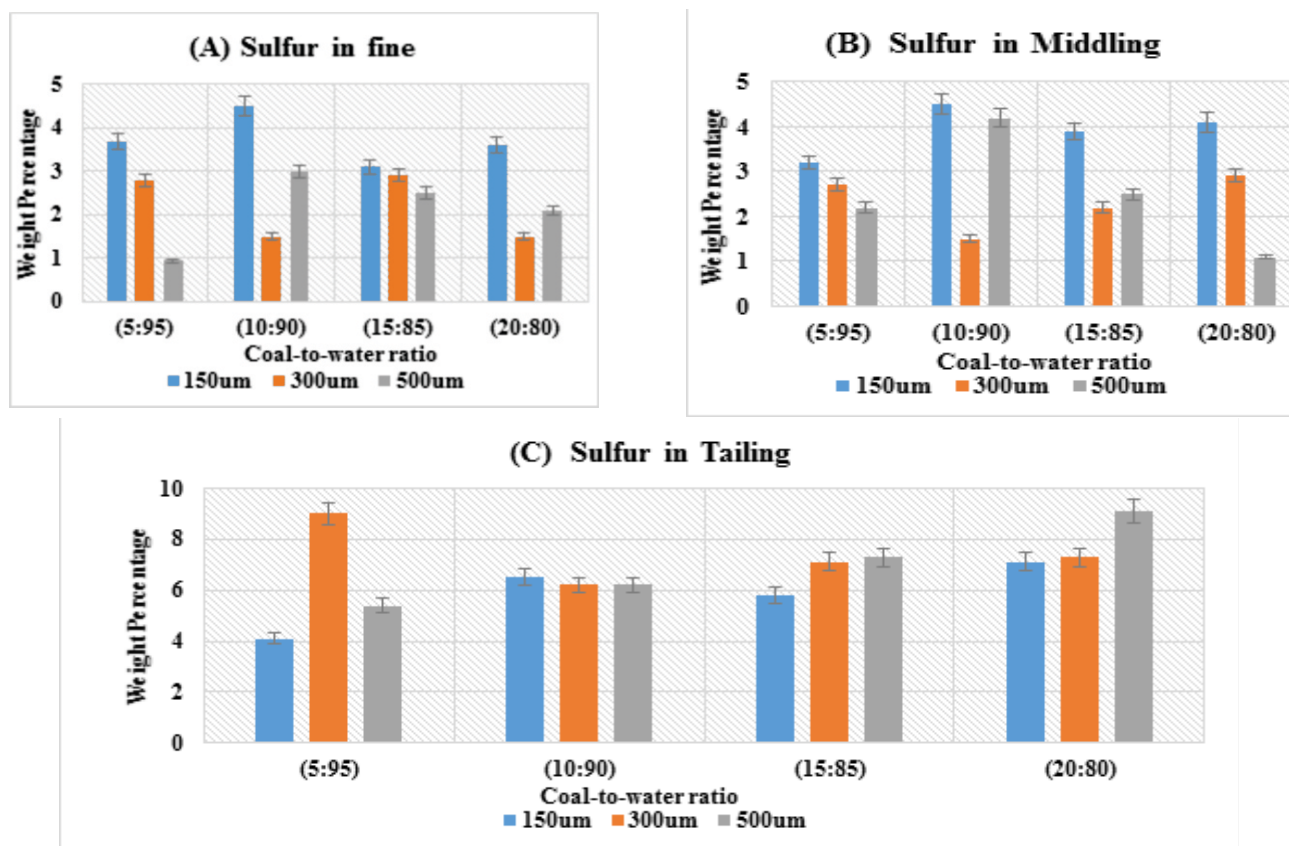


Figure 3: Reduction in sulfur content after cleaning by diester table

3.5 Effect on GCV:

Based on the sulfur and ash removal, GCV of the final products obtained from different positions of the diester table was also investigated. Lowest coal-to-water ratio yielded the best GCV (23.28 MJ/kg) which is the result of better pyrite and ash removal in case of this sample. The GCV of the middling fractions (21.81 MJ/kg) was found quite higher than that of tailing (17.11 MJ/kg). Comparison of the three fractions (tailing, middling and fines) indicates that fine is the cleanest fraction and tailing contain the most unclean coal. For all the coal-to-water ratios for 500 μm particle size, fine fraction has the highest GCV with 23.28 MJ/kg and tailing fraction has the lowest GCV with 14.54 MJ/kg in this study. This indicates that fines being

light in weight contains lesser impurities of ash and pyrite. Similarly, tailing is fraction concentrated in pyrite and mineral impurities resulting in lower GCV as shown in Fig. 4. It also signifies the potential of diester table used in this study to effectively separate the pyritic sulfur and other mineral matter impurities from coal. 500 μm coal was considered better coal sample for the removal of ash (88 wt%) and sulfur content (85 wt%) from a given coal sample.

The best coal-to-water ratio for 300 μm coal sample turned out to be 15:85 with the highest GCV of 16.29 MJ/kg. Lowest coal-to-water ratio (5:95) which was expected to produce the highest GCV but the resulted GCV was only 12.15 MJ/kg.

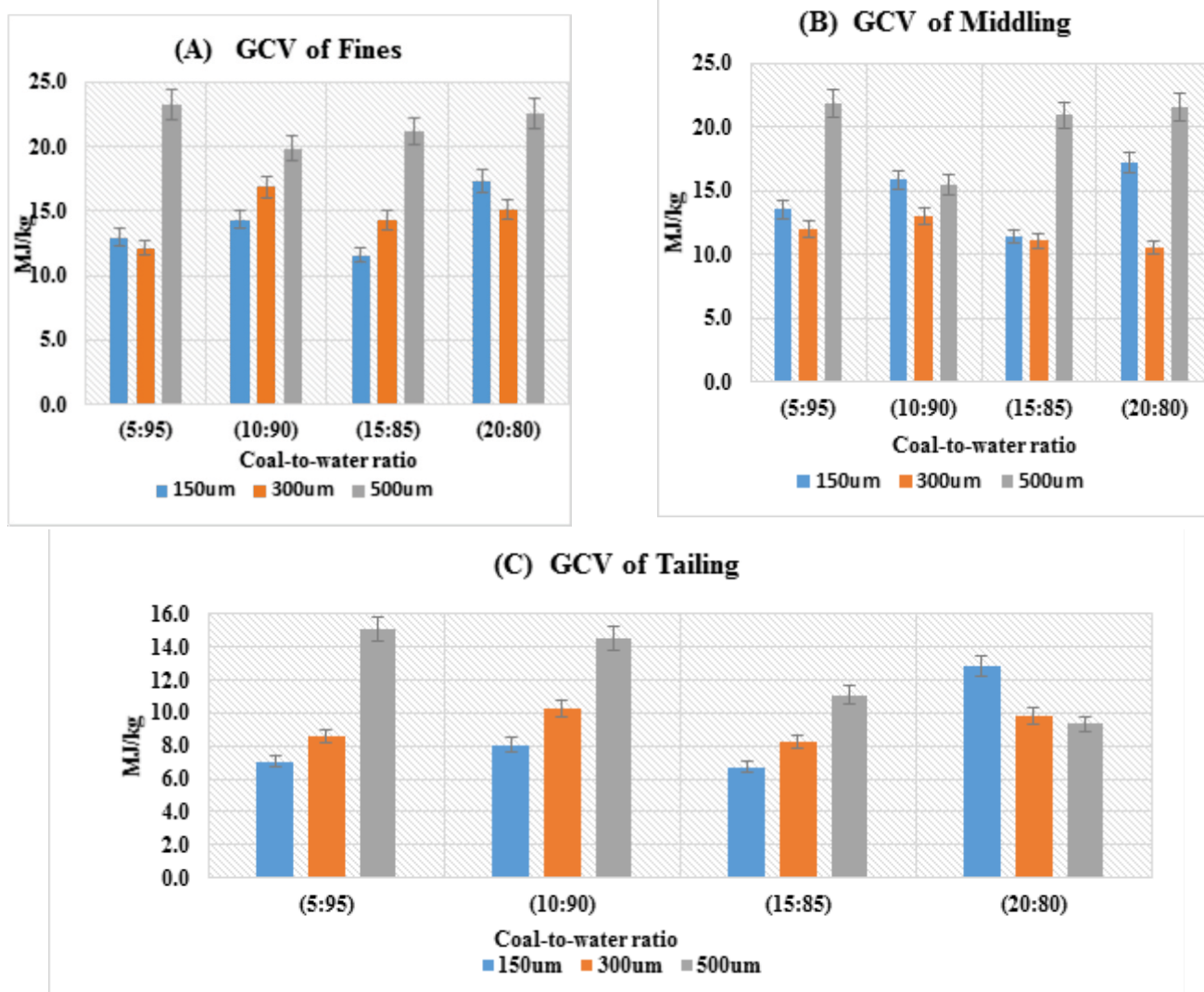


Figure 4: GCV of coal samples after cleaning by diester table

Similarly, for 150 μm coal size, among all the coal-to-water ratios, fine was the cleanest fraction having lowest ash and lowest sulfur content and hence producing highest amount of GCV. The best coal-to-water ratio for 150 μm coal sample appeared to be 20:80 with the highest GCV of 17.33 MJ/kg followed by 15:85 coal-to-water ratio which produced a GCV of 16.59 MJ/kg. Lowest GCV (14.33 MJ/kg) was obtained for coal-to-water ratio of 10:90. 150 μm coal size is so fine that density difference between mineral matter and coal particles is not sufficient for separation.

4. Conclusions:

The effect of two parameters, namely particle size and coal-to-water ratio on the sulfur removal efficiency of the diester was observed in this study. Particle sizes of 500 μm and 300 μm showed appreciable decrease in sulfur and ash content. However as the particle size was lowered to 150 μm , coal cleaning efficiency decreased significantly. This was primarily because of the decrease in density difference of coal and impurity as this technique relies on the difference in density which is maintained by large enough particle size. No clear correlation among the sulfur and ash removing efficiency of diester table with coal-to-water ratio was observed and it was because of lack of control over the amount of water used as additional water was also used to make coal particles flow over the diester table. Coal cleaning efficiency was also evaluated in terms of increase in GCV and lowest coal-to-water ratio of 5:95 yielded the best GCV of 23.28 MJ/kg for fines fraction of the products at 500 μm particle size.

References:

1. N. Nakicenovic, P. Kolp, K. Riahi, M. Kainuma, and T. Hanaoka, "Assessment of emissions scenarios revisited," *Environmental Economics and Policy Studies*, vol. 7, no. 3, pp. 137-173, 2006.
2. U. Ahmed, M.A. Hussain, M. Bilal, H. Zeb, U. Zahid, S.A. Onaizi, and A.G.A. Jameel, "Utilization of Low-Rank Coals for Producing Syngas to Meet the Future Energy Needs: Technical and Economic Analysis," *Sustainability*, vol. 13, no. 19, p. 10724, 2021.
3. G. Fettweis, *World coal resources: Method of assessment and result*. Elsevier, 2012.
4. Z. Asif, Z. Chen, H. Wang, and Y. Zhu, "Update on air pollution control strategies for coal-fired power plants," *Clean technologies and environmental policy*, pp. 1-19, 2022.
5. J. Ma, B. Zhong, M.A. Khan, D. Wu, Y. Zhu, Y. Wang, X. Xie, H. Liu, and D. Liu, "Transport of mobile particles in heavy metal contaminated soil with simulated acid rain leaching," *Bulletin of Environmental Contamination and Toxicology*, vol. 106, no. 6, pp. 965-969, 2021.
6. D. Wu, H. Zheng, Q. Li, L. Jin, R. Lyu, X. Ding, Y. Huo, B. Zhao, J. Jiang, and J. Chen, "Toxic potency-adjusted control of air pollution for solid fuel combustion," *Nature Energy*, vol. 7, no. 2, pp. 194-202, 2022.
7. R.W. Ward and G.M. DeGraeve, "Acute residual toxicity of several wastewater disinfectants to aquatic life 1," *JAWRA Journal of the American Water Resources Association*, vol. 14, no. 3, pp. 696-709, 1978.
8. A.M. Yadav, H. Singhal, D. Agarwal, and S. Suman, "Recovery of energy values from high-ash content washery tailings using waste oils by oil agglomeration," *Separation Science and Technology*, vol. 57, no. 8, pp. 1266-1278, 2022.
9. B. Liu, Q. He, Z. Jiang, R. Xu, and B. Hu, "Relationship between coal ash composition and ash fusion temperatures," *Fuel*, vol. 105, pp. 293-300, 2013.
10. Z. Ma, F. Iman, P. Lu, R. Sears, L. Kong, A. Rokanuzzaman, D.P. McCollor, and S.A. Benson, "A comprehensive slagging and fouling prediction tool for coal-fired boilers and its validation/application," *Fuel Processing Technology*, vol. 88, no. 11-12, pp. 1035-1043, 2007.
11. R. Meij, "Trace element behavior in coal-fired power plants," *Fuel processing technology*, vol. 39, no. 1-3, pp. 199-217, 1994.

12. D. Ghosh and S. K. Mitra, "High temperature corrosion problem of boiler components in presence of sulfur and alkali based fuels," *High Temperature Materials and Processes*, vol. 30, no. 1-2, pp. 81-85, 2011.
13. M. S. Malkani, A. M. K. MH, F. Buzdar, and M. Zahid, "Coal Resources of Pakistan: new coalfields," *Lasbela University Journal of Science & Technology*, vol. 5, pp. 7-22, 2016.
14. U. Ahmed, M. A. Hussain, M. Bilal, H. Zeb, N. Ahmad, N. Ahmad, and M. Usman, "Production of Hydrogen from Low Rank Coal Using Process Integration Framework between Syngas Production Processes: Techno-Economic Analysis," *Chemical Engineering and Processing - Process Intensification*, vol. 169, p. 108639, 2021.
15. M. R. Shah, M. S. Malkani, and A. A. Kakepoto, "Coal resources of Pakistan and their depositional environments," *Journal of Himalayan Earth Science*, vol. 45, no. 2, 2012.
16. B. Ackerman, W. T. Hassler, and W. T. Hassler, *Clean coal/dirty air: Or how the clean air act became a multibillion-dollar bail-out for high-sulfur coal producers*. Yale University Press, 1981.
17. R. T. Yang, S. K. Das, and B. M. Tsai, "Coal demineralization using sodium hydroxide and acid solutions," *Fuel*, vol. 64, no. 6, pp. 735-742, 1985.
18. T. Wheelock and R. Markuszewski, "Physical and chemical coal cleaning," in *AIP Conference Proceedings*, 1981, vol. 70, pp. 357-387: American Institute of Physics.
19. N. Pandian, C. Rajasekhar, and A. Sridharan, "Studies of the specific gravity of some Indian coal ashes," *Journal of testing and evaluation*, vol. 26, no. 03, pp. 177-186, 1998.
20. S. Wang, Q. Xia, and R. Gao, "Cleaning high ash coal waste from coking coal via froth flotation method," *Particulate Science and Technology*, pp. 1-13, 2021.
21. H. Sana, M. A. Hussain, R. Mujahid, A. Riaz, M. S. Akram, B. Haider, A. Ahsan, S. Kanwal, and H. Zeb, "Cleaning of Thar Coal by Froth Flotation and Water," *Journal of the Pakistan Institute of Chemical Engineers*, vol. 50, no. 2, 2023.
22. O. S. A. Williams, P. Daley, J. Perkins, K. L. Martinez-Mendoza, J. Guerrero-Perrez, L. M. S. Mazabuel, E. A. G. Saavedra, M. Trujillo, J. Barraza-Burgos, and M. Barajas, "Upgrading of Low-Grade Colombian Coals via Low-Cost and Sustainable Calcium Nitrate Dense Media Separation," *ACS Omega*, 2022.
23. S. Chakladar, A. K. Mohanty, and S. Chakravarty, "Oil Agglomeration Towards Quality Enhancement of High-Ash Coals: The Indian Scenario," in *Clean Coal Technologies: Springer*, 2021, pp. 71-82.
24. M. I. Alonso, A. F. Valdés, R. M. Martínez-Tarazona, and A. B. Garcia, "Coal recovery from coal fines cleaning wastes by agglomeration with vegetable oils: effects of oil type and concentration," *Fuel*, vol. 78, no. 7, pp. 753-759, 1999.
25. A. B. Garcia, J. G. Vega, and M. R. Martínez-Tarazona, "Effects of oil concentration and particle size on the cleaning of Spanish high-rank coals by agglomeration with n-heptane," *Fuel*, vol. 74, no. 11, pp. 1692-1697, 1995.