Dry coal beneficiation of high-ash South African coal utilising a wind sifter separator

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Abstract. Beneficiation of high-ash South African coal is challenging, especially in water-scarce regions, amid increasingly stringent environmental regulations. Traditional wet methods, although effective, are unsustainable due to excessive water consumption and high waste slurry generation. Accordingly, this study focusses on evaluating a wind sifter separator for the dry beneficiation of high-ash run-of-mine (ROM) coal, classified into three particle size distributions (PSD's): (−6.7+3.35 mm), (−3.35+1 mm), and (−1+0.2 mm). By applying aerodynamic principles, the wind sifter separates coal based on density and size variations, which provides an alternative to water-based techniques. The wind sifter separator was able to reduce the ash content of the feed coal (37.4 wt. % ash) to 16.7%, with mean probable error (Ep) values of 0.035 to 0.16, depending on airstream velocity. The separator demonstrated operational flexibility by performing efficiently with and without bin collection. The results obtained indicate substantial ash removal while maintaining significant clean coal recovery, offering a viable dry beneficiation solution for water-limited regions. When compared to conventional wet beneficiation and other dry techniques, the achieved balance between ash reduction and energy (or combustible matter) recovery underscores its competitive performance. Furthermore, its design suggests potential uses beyond coal, such as pre-concentration and upgrading of other minerals, which makes it a promising breakthrough for sustainable mineral processing.

1 Introduction

Energy resources are fundamental to global socio-economic growth and industrial advancement, with coal continuing to serve as a dominant primary energy source, particularly in coal-abundant countries. [1-2]. Despite the shift to cleaner alternatives, coal still accounts for nearly one-third of global power generation and is projected to dominate electricity production in over 80 countries by 2040 [1-3]. Rapidly industrialising nations like China and India sustain high coal consumption, with China alone consuming over 50% of global coal, primarily for steel production and power generation [4]. The depletion of high-quality coal reserves necessitates the beneficiation and use of lower-grade coal to meet energy demands [5].

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In Southern Africa, coal remains the primary energy source, driving economic growth and industrialisation. Nearly 70% of South Africa's electricity is generated by coal, and local (South Africa's) reserves are estimated to last over 100 years at the current rate of extraction [7]. Maintaining coal quality is crucial for metallurgy and power generation, prompting research into advanced beneficiation technologies [8–10]. Coal beneficiation, using wet or dry methods, removes inorganic minerals to meet industrial standards while ensuring environmental compliance.

Conventional wet beneficiation techniques - such as jigging, froth flotation, and spirals - are widely used due to their ability to produce high-grade clean coal with significant recovery rates [11–16]. However, challenges such as water scarcity, water accessibility, wastewater management, and high capital and operational costs have led to a growing preference for dry beneficiation, particularly for fine coal upgrading [17]. Dry beneficiation preserves coal's heating value by eliminating the need for drying and exploits physical properties such as size, density, electrical conductivity, and magnetic susceptibility for separation [18–21].

Several dry beneficiation techniques have been developed, including air tables, pneumatic separators, and air-dense medium fluidised beds. Tribo-electrostatic separators exploit differences in charge accumulation, while air jigs utilise oscillatory airflow for density-based separation [19, 22–23]. Air-jet separation has also shown promise; for instance, Yang *et al*. (2018) [27] used a planar air-jet separator to beneficiate coal in the (-6 +2 mm) size range, achieving a 16.8% ash content with a 56.8% yield from a feed coal with 26.9% ash. Dong *et al*. (2022) [28] demonstrated the effectiveness of combining ADMFB and FGX dry separators, achieving optimal separation at an air velocity of 0.11 m/s with a resultant coal ash content of 7.86% and a yield of 90.96%.

Recent advancements in dry beneficiation have enhanced separation efficiency, reduced energy consumption, and improved adaptability for various coal types [20–21, 28–30]. This study investigates a laboratory-scale zigzag wind-sifter separator for beneficiating high-ash South African coal. Previous studies by Alade et al. (2021) [21] and Alade, (2020) [31] validated the technology's effectiveness, reducing coal ash content from 30.3% to 16.8%. The abovementioned studies offer detailed insights into the prototype separator for dry coal beneficiation, while the present study focuses on an optimised wind-sifter design for enhanced performance. In addition, this study also emphasises the zigzag configuration, while alternative designs have been extensively examined by Alade and Bada (2023) [32].

2 Method

2.1 Separator design

The wind-sifter separator was designed in Autodesk Inventor, establishing its structural and functional framework. Simulation analysis in Star-CCM+ evaluated separation parameters such as buoyant and drag forces, particle properties, airstream velocity, and air-jet angle. This approach optimised separation efficiency and clean coal recovery. Figure 1 illustrates the framework and structured approach that was followed during this study.

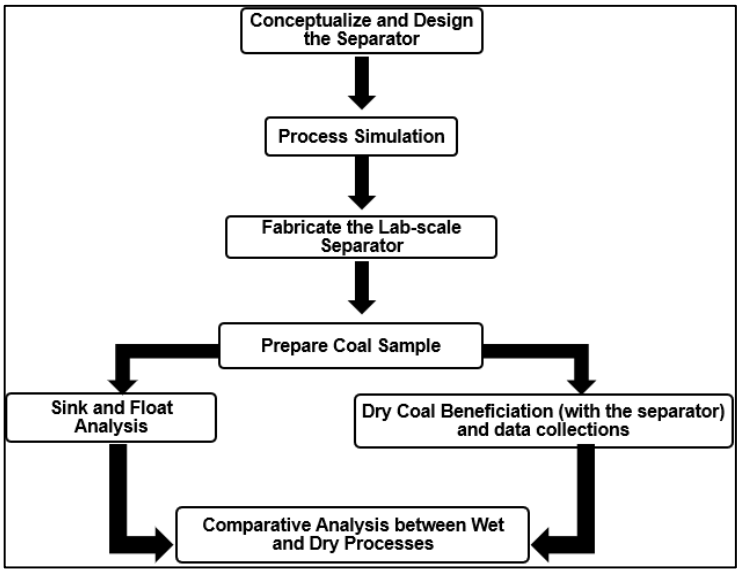

Fig. 1. A schematic representation of the study's workflow.

Following Alade, (2020) [31], a 0.6 g/s mass flow rate ensured dilute-phase loading, minimising particle interactions. Airflow was modelled as a continuous steady-state phase, with force resolution at discrete points. Spatial variations were negligible, allowing uniform fluid density. Alade et al. (2025a) [21] further examined the effects of governing equations and particle properties on separation.

2.2 The fabricated separator

The optimised wind-sifter separator (excluding auxiliaries) measures 2.5 m (Lenth) × 1.3 m (Height) × 0.2 m (Width). Along with auxiliaries, the dimension is 4 x 2.5 x 0.9 m. The separator is mounted on a cradle for flexibility and can be operated with or without product collection bins. Alade et al. (2025a;2025b) [21, 30] detail its design, fabrication, and operating principle. Figures 2 and 3 present the separator's design model and its corresponding fabricated unit, respectively.

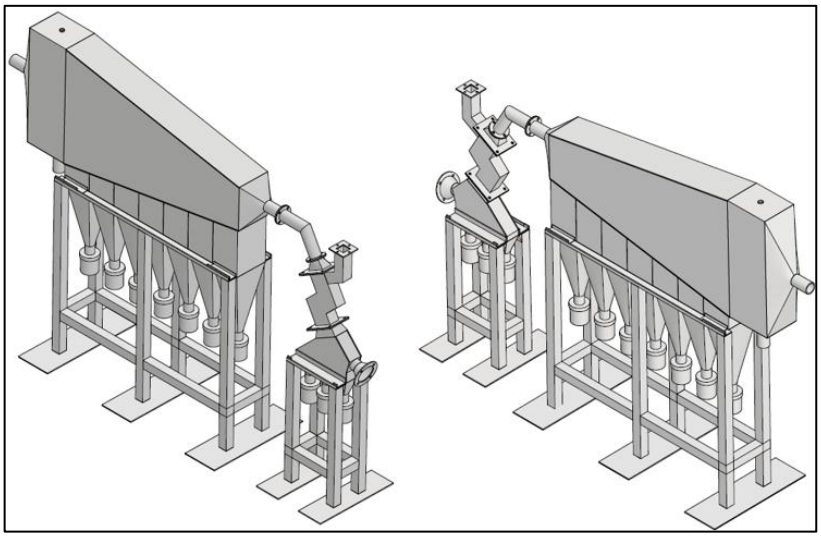

Fig. 2. The optimised wind-sifter separator assembly design

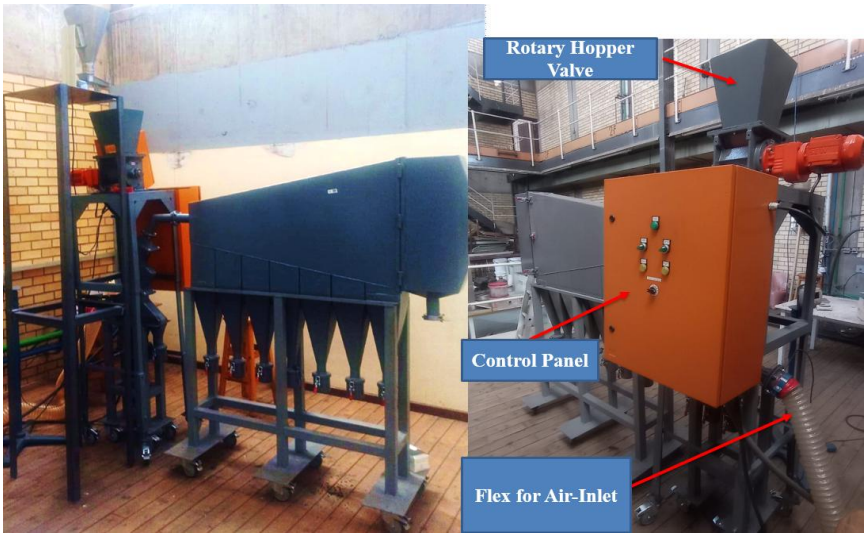

Fig. 3. The fabricated separator assembly setup

2.3 Experimental analysis

The study utilized ROM coal that was obtained from the Witbank Coalfield area, located in Mpumalanga Province, South Africa. The as received coal was crushed and classified into three size fractions (-6.7+3.35 mm, -3.35+1 mm, and -1+0.2 mm). Representative feed coal samples were obtained using a static sampler according to ASTM D2013 standards.

2.3.1 Float-sink analysis

The coal sample was subjected to float-sink tests in accordance with ASTM-D4371 and ISO 7936:1992 standards. Zinc chloride solutions with relative densities (RDs) from 1.3 to 1.8 (0.1 increments) were prepared in six individual 5 L beakers. A digital density meter ensured RD accuracy. A 500-g coal sample was analysed to construct a washability profile, with separation efficiency assessed via mean probable error (Ep) using Equation 1.

$$E_P = \frac{D_{75} - D_{25}}{2} \qquad (1)$$

Where D_{75} is the RD at which 75% of the particles report to the sinks, and D_{25} is the RD at which 25% of the particles report to the sinks.

2.3.2 Dry coal beneficiation using the separator

Dry beneficiation tests followed float-sink analysis for the three particle-size distributions. The separator was tested with and without collection bins. Air velocities ranged from 6–4 m/s for (-6.7+3.35 mm), 4.2–2 m/s for (-3.35+1 mm), and 1.7–0.5 m/s for (-1+0.2 mm), based on Alade et al. (2021) [20] was used. Secondary-separation phase test targeted (-6.7+3.35 mm) and (-3.35+1 mm) to minimise ash content. Without **product collecting bins**, higher velocities were tested: 10.5 and 9 m/s (-6.7+3.35 mm), 7 and 5 m/s (-3.35+1 mm), and finally, 3.5 and 2.5 m/s (-1+0.2 mm), as per Alade et al. (2025a) [21]. A comparative analysis was performed between this optimised wind-sifter separator and the initial prototype design outlined by Alade et al. (2025a) [21] and Alade, (2021) [31] to assess advancements in separation efficiency and overall performance. This evaluation aimed to quantify the extent to which the optimised separator improved coal beneficiation, particularly regarding coal product yield and beneficiation effectiveness. Section 3.3.6 provides the results of the comparison between the prototype and optimised separator designs.

2.3.3 Analytical techniques

Proximate, ultimate, and calorific value analyses were performed in accordance with ASTM standards. Proximate analysis was done with TGA 701 equipment (ASTM D7582-15), while ultimate and sulphur analyses were conducted with LECO CHN 628 (ASTM D5373-14, ASTM D4239-14). Calorific values were determined via a Leco AC 500 bomb calorimeter (ASTM D5865-04), focusing on samples with minimal ash content.

2.3.4 Effect of moisture

The impact of moisture on separation was tested using 500g coal samples from (-6.7+3.35 mm) and (-3.35+1 mm) fractions, excluding (-1+0.2 mm) due to prior mass loss. Samples were immersed in water for 10 minutes, then dried at ambient temperature for 24, 18, 12, or 6 hours, and subsequently fed into the separator. Mass and residual moisture were measured before separation, and losses were recorded post-process. Moisture content, adjusted for drying time, was calculated using **Equation 2** to assess its effect on separator performance and product recovery.

$$\left(\frac{\text{Mass of IM in Dry Coal (Without additional moiture)}+(\text{New mass}-\text{Old mass})}{\text{New Mass}}\right)*100\% \quad (2)$$

Where IM is Inherent Moisture

3 Results

3.1. Results from sink-float analysis

Float-sink analysis showed the (-1+0.2 mm) coal had the lowest ash content (4.3% at 1.3 RD), followed by -3.35+1mm at 5.6% and -6.7+3.35 mm at 5.9%. This supports the principle that finer particles achieve better liberation [33, 34]. Cumulative yields at 1.8 RD ranged from 59.9% (coarsest) to 73.3% (finest), indicating a high concentration of mineral-rich particles. Feed coal ash content for (-6.7+3.35 mm), (-3.35+1 mm) and (-1+0.2 mm) was 37.4%, 31.1%, and 29.3%, respectively.

3.2. Wind-sifting beneficiation

Prior to conducting any analyses on the wind-sifter separator, the coal feeder was calibrated, and repeatability tests were carried out to ensure consistent operation. These procedures are thoroughly documented in the study by Alade et al. (2025b) [30]. In all figures**, the bars illustrate the cumulative ash content**, while **the trend lines depict the cumulative yield** progression.

3.2.1 Beneficiation results (with collection bins)

Wind-sifter tests incorporating collection bins revealed a significant correlation between air velocity and beneficiation efficiency. Key findings per size fraction are deliberated on in this section.

For (-6.7+3.35 mm), 6 m/s air velocity yielded 77.4% coal with 27% ash content. Reducing to 5 m/s improved ash content (24.8%) but lowered yield (62.6%). At 4 m/s, ash decreased to 19.1%, while yield increased to 31.17% (Figure 4). Similarly, for (-3.35+1 mm), 4.2 m/s gave 83.4% yield at 27.3% ash, while 3 m/s reduced ash (24.1%) but also yield (71.6%). At 2 m/s, ash content reached 20.5%, though yield fell to 28. 9% (Figure 5). For (-1+0.2 mm), 1.7 m/s achieved 95.8% yield at 26.7% ash. Lowering to 1 m/s improved separation (25.2% ash, 42.1% yield), while 0.5 m/s resulted in 19.6% ash but a reduced 14.3% yield (Figure 6). This phenomenon is also backed up from the literature from multiple studies, including studies conducted by Çicek, (2008) [33].

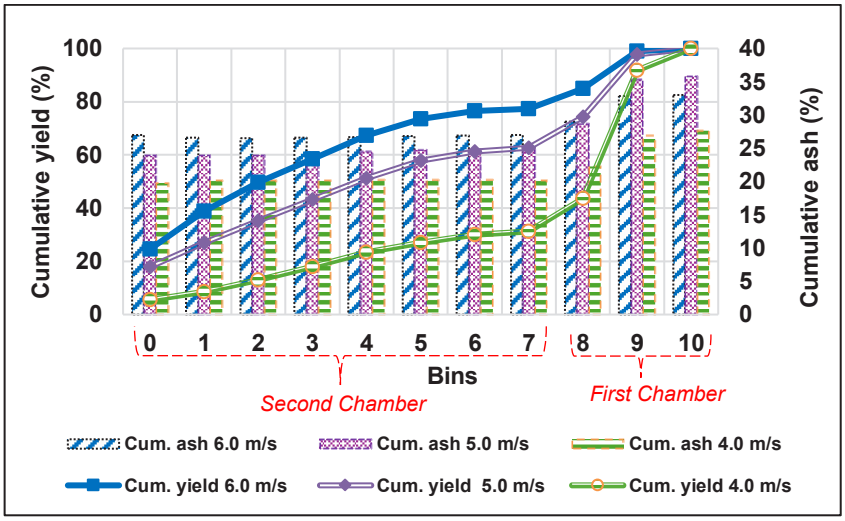

Fig. 4. Cumulative ash and yield for (-6.7+3.35 mm) at varying airstream velocities (with collection bins)

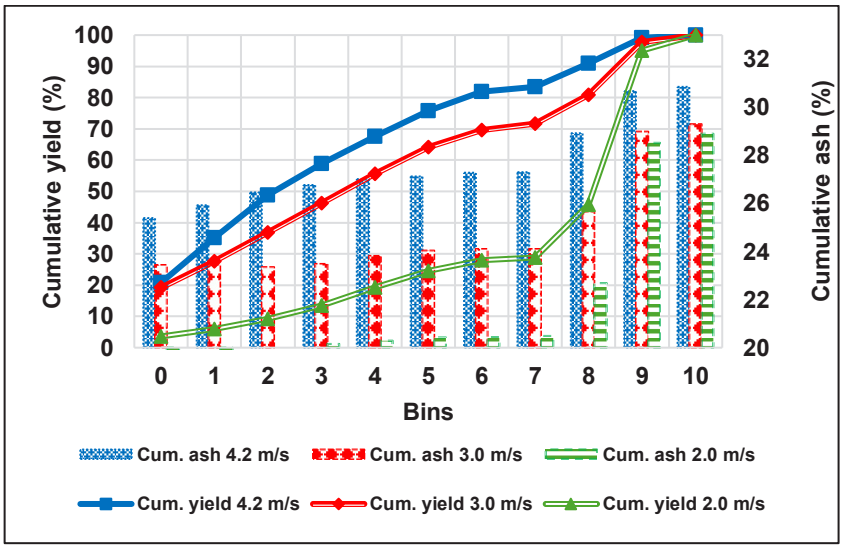

Fig. 5. Cumulative ash and yield for (-3.35+1 mm) size distribution at varying air velocities (with collection bins)

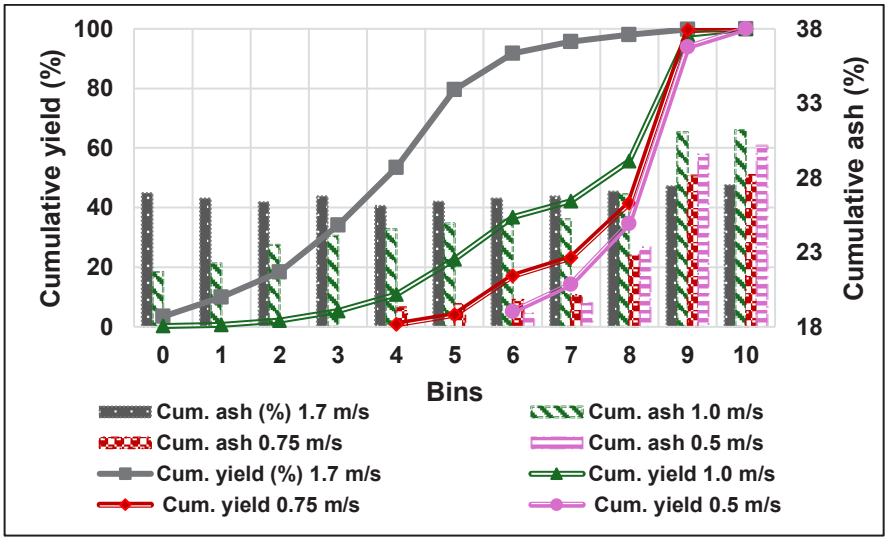

Fig. 6. Cumulative ash and yield for the (-1+0.2 mm) distribution size at varying airstream velocities (with collection bins)

A secondary separation phase test was conducted using air velocities of 5 m/s and 4 m/s for the (-6.7+3.35 mm) size fraction, and 3 m/s and 2 m/s for the (-3.35+1 mm) fraction. For each particle size distribution, 500 g of coal was initially charged into the separator. The combined outputs from chamber 2 and rejects from chamber 1 were reprocessed. First-stage outputs from bins 0–7 served as feed for the secondary separation, while bins 8–10 formed a separate feed.

For (-6.7+3.35 mm), 5 m/s air velocity yielded 79. 8% coal and 21.8% ash, while 4 m/s improved ash content (19.52%) but reduced yield (52.60%). **At 5 m/s, the product and discard masses were 278.0 and 212.7 g, while at 4 m/s, they were 170.5 and 328.8 g** (Figure 7a & b)**.** For (-3.35+1 mm), 3 m/s achieved 86% yield at 20.9% ash, while 2 m/s improved ash (19.8%) with 82.6% yield. Product/discard masses were 293.7 and 198.7 g at 3 m/s and 143.8 and 354.2 g at 2 m/s (Figure 8a & b). The secondary separation phase test effectively reduced ash while maintaining yield.

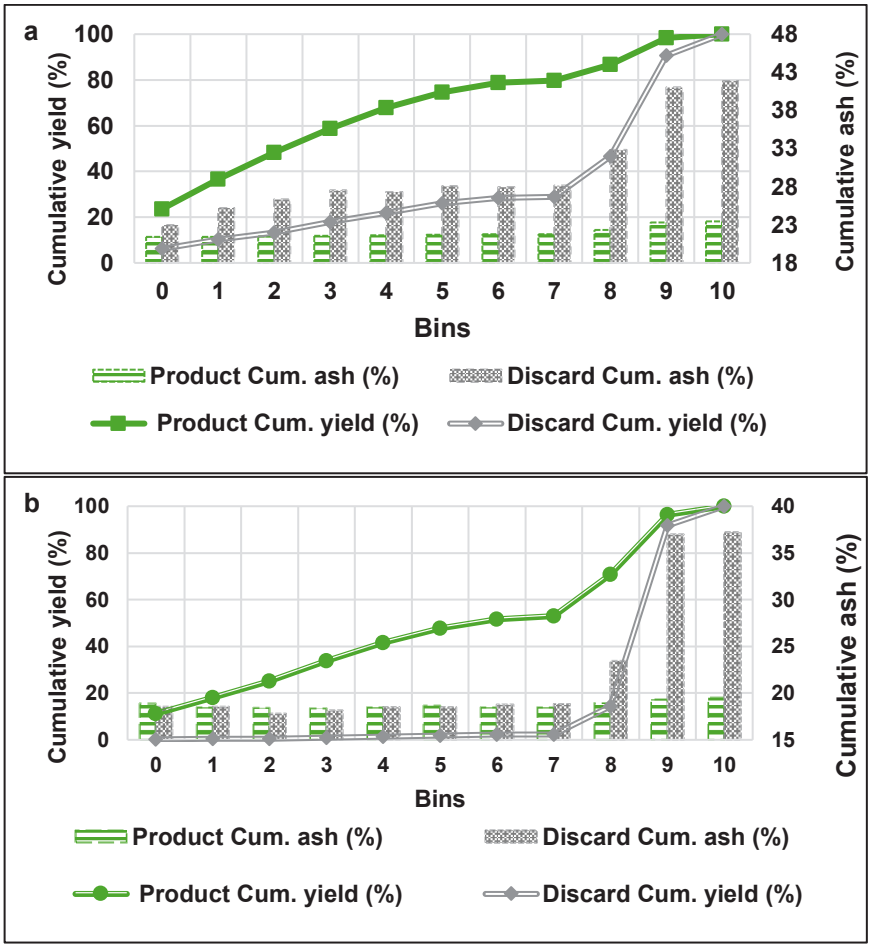

Fig. 7(a & b). Secondary-separation phase test of the (-6.7+3.35) mm size distribution at air velocities of 5 and 4 m/s.

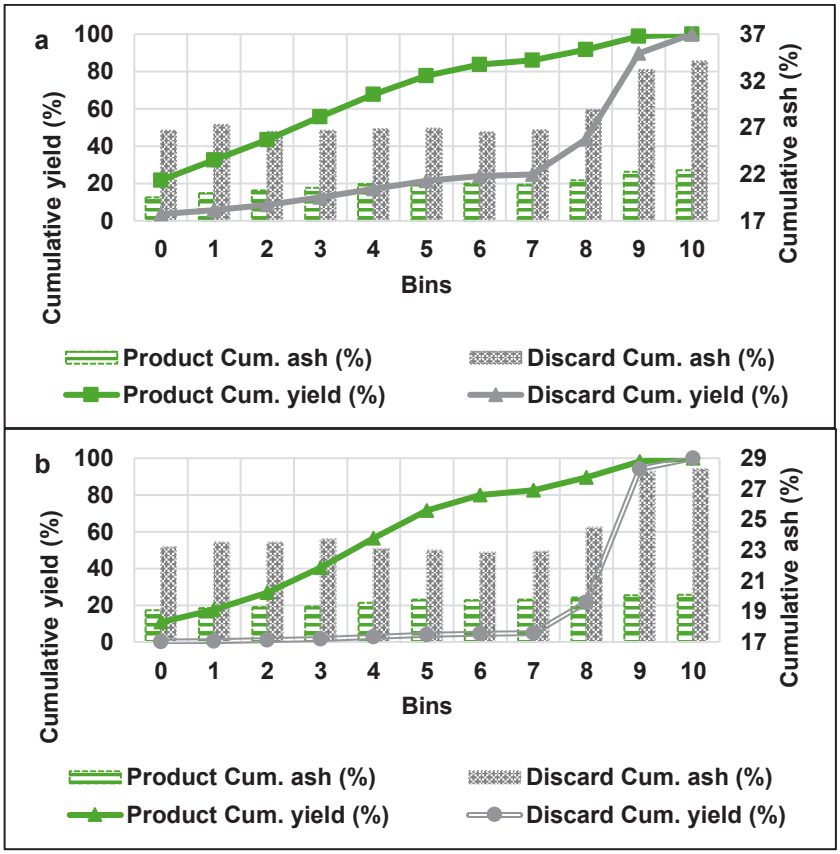

Fig. 8(a & b). Secondary-separation phase test of the (-3.35+1) mm size distribution at 3 and 2 m/s air velocities.

3.2.2 Beneficiation results (without collection bins)

Separation outcomes for the (−6.7+3.35 mm) size at air velocities of 10.5 m/s and 9 m/s are shown in Figure 9. Figure 10 shows the results for (−3.35+1 mm) at 7 m/s and 5 m/s air velocities, while Figure 11 depicts the results for the finest size distribution at 3.5 m/s and 2.5 m/s. For (−6.7+3.35 mm), coal product with cumulative ash and yield of 22.5% and 58.4% respectively was recovered at 10.5 m/s. By lowering the air velocity to 9 m/s, a coal product with cumulative ash and yield of 19.4% and 36.9% respectively was achieved. For (−3.35+1 mm), a coal product of 23.8% cumulative ash and 62.7% cumulative yield was achieved at 7 m/s. At 5 m/s, the ash content decreased to 20.9%, leading to a product yield of 29%. For the finest size distribution, using 3.5 m/s air velocity, a coal product with a cumulative ash content of 27.9% and a cumulative yield of 91.3% was recovered**.** The reduction in the air velocity to 2.5 m/s resulted in an ash content of 22.7% and a product yield of 68.2%.

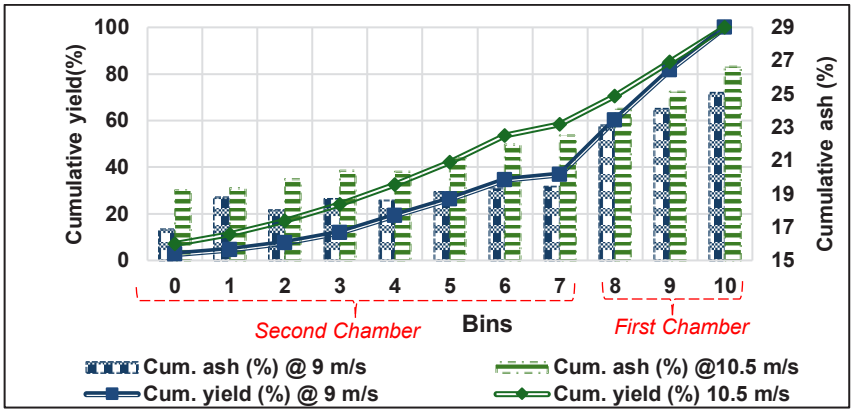

Fig. 9. Cumulative ash and yield for the (-6.7+3.35) mm size distribution at different airstream velocities (without collecting bins)

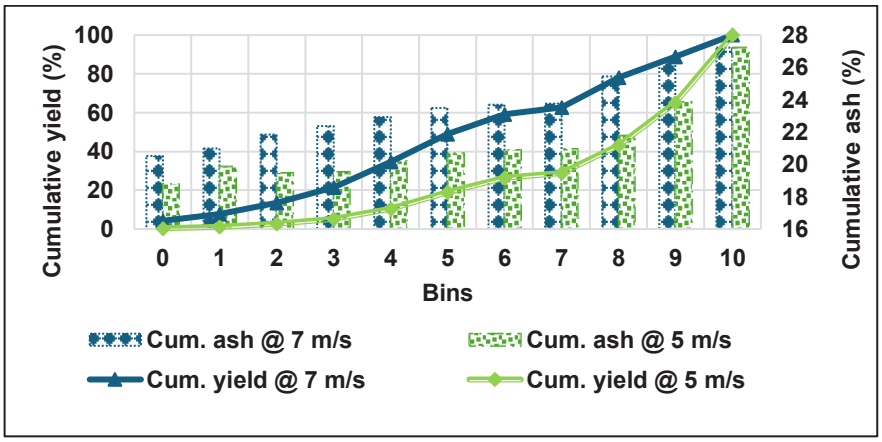

Fig. 10. Cumulative ash and yield for the (-3.35+1) mm size distribution at different airstream velocities (without collecting bins)

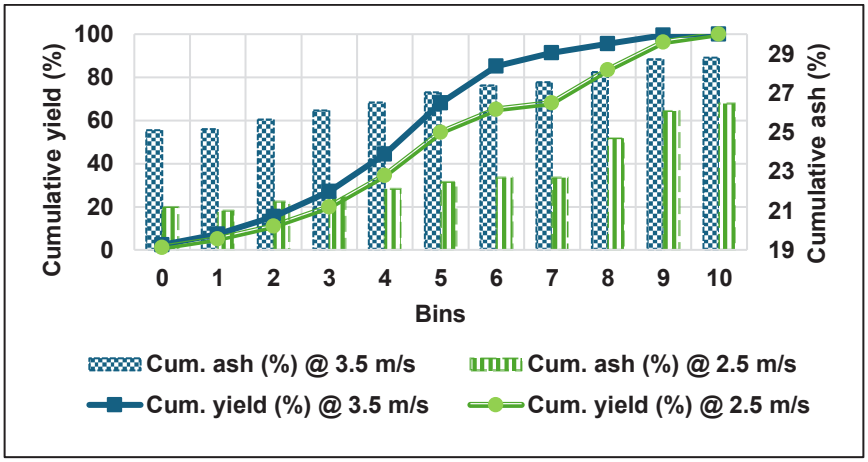

Fig. 11. Cumulative ash and yield for the (-1+0.2) mm size distribution at different airstream velocities (without collecting bins)

3.2.3 Performance comparison (optimised vs. prototype separator)

A comparative analysis between the optimised wind-sifter separator and the prototype system revealed significant enhancements in beneficiation efficiency. For the coarsest size distribution, the optimised separator achieved a 77.4% cumulative yield in chamber 2 at an air velocity of 6 m/s, compared to 58.4% in the earlier design [31]. The previous design exhibited 7.4% of sample loss, whereas the optimised separator reduced this loss to 2.6% at 4 m/s, and further to 1% in second chamber of the separator assembly. Similar trends were observed across other particle size distributions; for the (-3.35+1 mm) size distribution, the optimised design exhibited sample loss ranging from 0.32 to 2.7%, significantly lower than the 3.5 to 10.5% losses recorded with the previous design. The finest size distribution experienced sample losses of 2.3 to 7.1% in the optimised separator, which marked an improvement compared to the previous design, where more than 50% of the sample became trapped within the system. This highlights the enhanced sifting efficiency to achieve significantly reduced material loss with the optimised separator.

3.2.4 Evaluation of the beneficiation performance of the optimised separator

The separation efficiency was evaluated based on the E_P values, which is indicative of operational sharpness. It was observed that lower air velocities generally corresponded to increased E_P values, reflecting a trade-off between ash reduction and yield. The optimised wind-sifter separator demonstrated superior performance compared to conventional dry beneficiation techniques, with E_P values ranging between 0.035 and 0.16. This compares favourably with established dry beneficiation methods such as the FGX technology with E_P values typically range between 0.20 and 0.30 [23, 35]. E_P values of the Air-jig separator range within 0.16–0.30 [36-38] and 0.18–0.65 was attained for the Air-table [26]. Results are presented in Figures 12, 13 and 14.

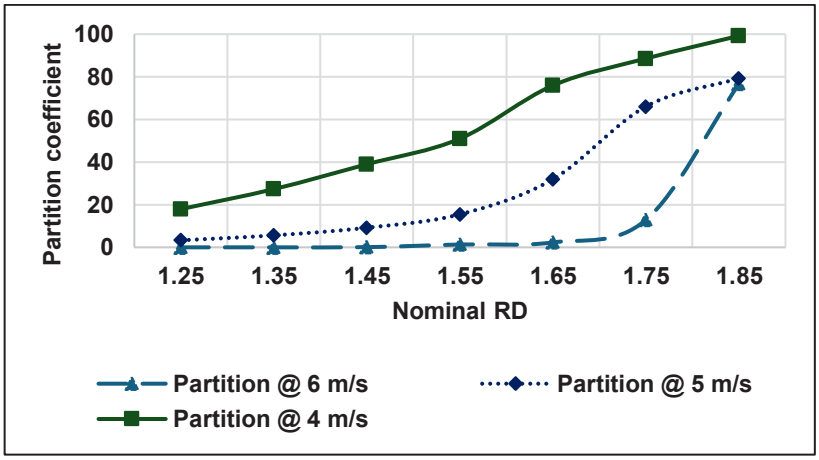

Fig. 12. Partition curves for the (-6.7+3.35) mm size distribution

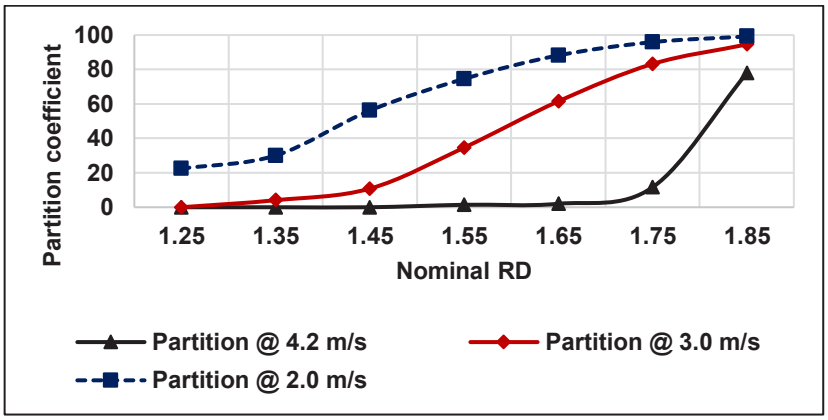

Fig. 13. Partition curves for the (-3.35+1) mm size distribution

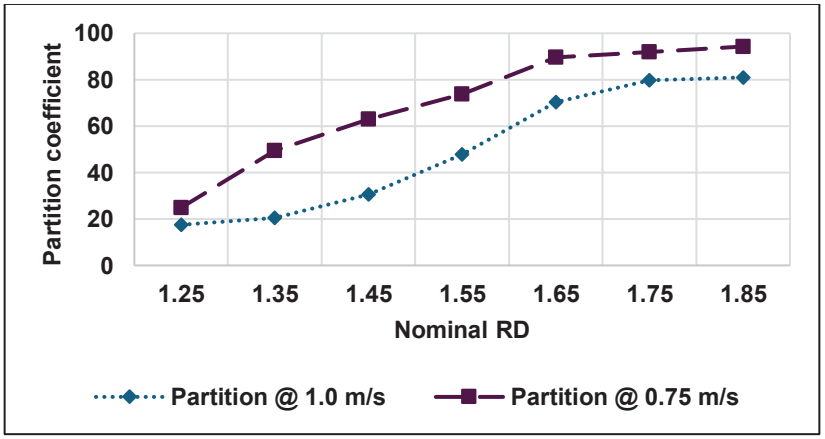

Fig. 14. Partition curves for the (-1+0.2) mm size distribution

3.2.5 Effect of moisture

Figures 15 and 16 show results for (-6.7+3.35 mm) and (-3.35+1 mm) coal with inherent moisture of 2% and 3% (air-dry basis), respectively, using 500 g feed.
For (-6.7+3.35 mm), 24-hour drying (2% moisture) yielded 520 g (5.8% moisture) with 0.3% mass loss. At 18 hours (533.3 g, 8.1% moisture), 1% was lost. The 12-hour sample (549.2 g, 10.8% moisture) lost 7%, while the 6-hour sample (592.8 g, 17.3% moisture) had 52.8% loss due to adhesion of particles to the separator walls. For (-3.35+1 mm), 24-hour drying (512.2 g, 5.3% moisture) lost 1.1%. The 18-hour sample (520.2 g, 6.8% moisture) lost 3.5%, while the 12-hour sample (534.9 g, 9.3% moisture) lost 21%, **which led to the termination** of further tests. Acceptable moisture levels are ≤8% for (-6.7+3.35 mm) and ≤6% for (-3.35+1 mm).

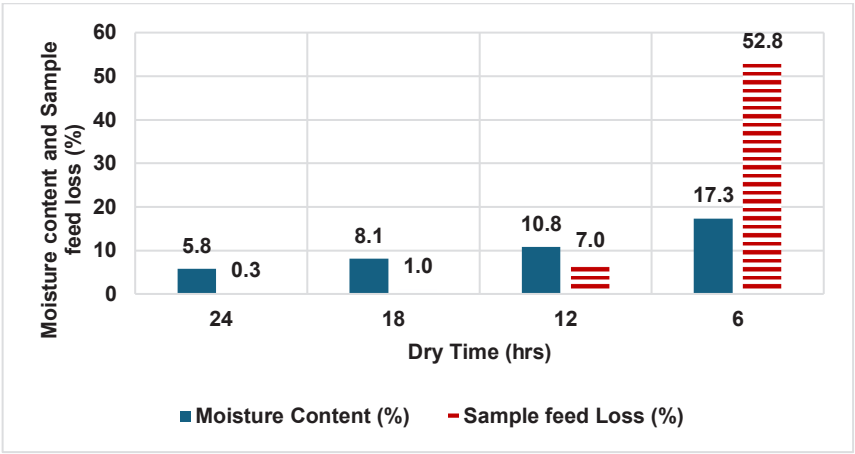

Fig. 15. Effect of moisture on the (−6.7+3.35 mm) size distribution

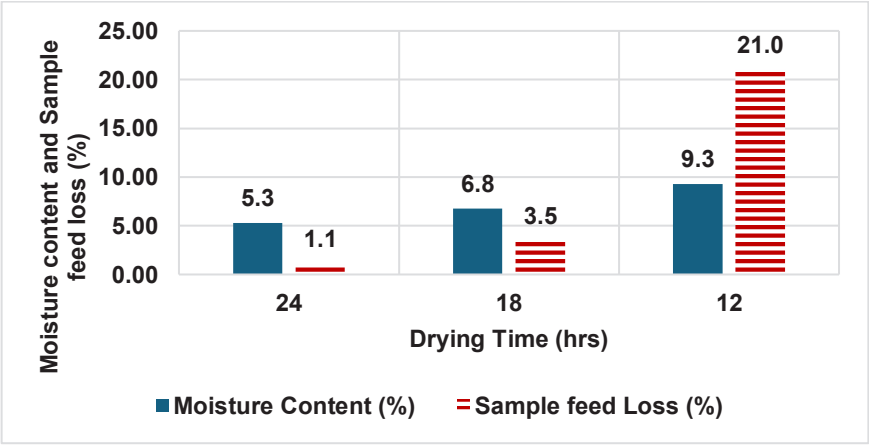

Fig. 16. Effect of moisture on the (−3.35+1 mm) size distribution

4 Conclusion

The optimised wind-sifter separator demonstrated a marked improvement in dry coal beneficiation, achieving significant ash reduction with minimal material loss. The integration of a secondary separation phase has further enhanced beneficiation efficiency, allowing for greater flexibility in processing different coal feed qualities.

Overall, the study confirms the wind-sifter's potential as a viable and effective alternative to conventional dry coal beneficiation methods. The findings provide valuable insights into optimising air velocity settings for maximising separation efficiency while maintaining a balance between ash content reduction and product yield. Future research could focus on further refinements in separator design and operational parameters to enhance industrial-scale applications of this technology.

Credit author statement: **Jimmy Alade**: Methodology, Validation, Investigation, Formal Analysis, Visualization, Writing – Original Draft. **Orevaoghene Eterigho-Ikelegbe**: Visualization, Writing – Review & Editing. **Samson Bada**: Conceptualization, Validation, Resources, Supervision, Visualization, Project administration, Funding acquisition, Writing – Review & Editing.

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