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A review of the dry methods available for coal beneficiation

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ABSTRACT

Water is a precious global resource that is important in most currently employed coal beneficiation practices. These widely accepted processes deliver consistent and precise separation efficiencies at desired product yields and throughputs. Although favoured, the water usage related to wet processing may be impractical and unsustainable in certain regions. Consequently, present-day practices used in coal processing may soon have to adapt, irrespective of any improved technical and economic feasibility offered. Therefore, the development of efficacious dry beneficiation methods has become an appealing research topic.

This review assembles information pertaining to the principle and success of commercially available and experimental phase dry processes applicable to coal beneficiation. These methods show much potential and, with some consideration of possible limitations and further investigation, may be established in future in the especially arctic, arid, and under-developed regions through new plant installations, expansions, and small mines and fines processing.

1. Introduction

Coal is a key component in energy production and is, therefore, instrumental in economic development globally. Typically, coal requires processing to remove any gangue minerals. This increases the coal quality, reduces greenhouse gas emissions, and lessens transportation and waste disposal costs (Van Houwelingen and De Jong, 2004; Fu et al., 2019).

Coal preparation techniques depend on wet separation processes such as cyclones, spirals, and floatation cells. These require large amounts of water and incur high operating expenses (Jambal et al., 2016). Moreover, many countries (such as China, India, South Africa, Russia and Turkey) experience water scarcity, and obtaining authorization for industrial use is becoming increasingly challenging (Lv et al., 2018; Zhu et al., 2019; Zhou et al., 2019). Therefore, wet processing methods may not be feasible in remote, under-developed or arid regions and areas with long periods of freezing temperatures. As a result, replacing wet separation techniques with alternative dry processes has been encouraged.

Dry beneficiation methods have some remarkable benefits when compared to wet methods. They are intriguing to the coal industry due to the following: water scarcity, higher heating value, low capital and operational costs, low transportation costs, reduced environmental impacts related to water consumption and pollution, and developing coal mines in arid regions (Von Ketelhodt and Bergmann, 2010; Jambal et al., 2020). These processes do not utilize water, and post-processing for dewatering and wet waste disposal is unnecessary. Moreover, they are compact, modular, and easy to erect, making them suitable for remote and under-developed areas (Weinstein and Snoby, 2007; Tomra, 2017).

Dry beneficiation processes have numerous advantages, but any associated limitations must be considered. Successful separation is obtainable, but the efficiency and throughput may not always compare to what is achievable in a wet processing plant. "Consequently, coal beneficiation plants operating on exclusively dry techniques is a goal that is yet to be completely achieved", as Hughes et al. (2019) stated. Therefore, most are currently limited to regions with extreme environmental conditions and find use in pre-concentration applications, scavenging, operations in small or remote reserves, beneficiation where the coal does not require much upgrading and finally, for "easy to separate" coals. One of the challenges for dry coal processing operations is the moisture content in run-of-mine (ROM) coals because of the water used in dust subduing (Weinstein and Snoby, 2007). Moreover, processing lower ore grades at finer particle sizes and large capacities has become necessary to meet the demand for good-quality coal. (Honaker et al., 2008).

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Given the recent economic and environmental drives for dry coal beneficiation globally, many research efforts have attempted to ameliorate any formerly observed shortfalls (in terms of efficiency, capacity, and yield). Much investigation has since been conducted into these processes, and improvements have been made to some previously abandoned methods, such as pneumatic concentrators and sensor-based sorters (Manoucherchi, 2003; Weinstein and Snoby, 2007). Some state-of-the-art techniques have emerged, including fluidized bed separators (De Korte, 2013; Chen and Wei, 2005; Zhang et al., 2014; Zhang et al., 2017; Diedericks et al., 2022), suction fluidization treatments (Stepanenko, 2016a; Stepanenko, 2016b; Stanczyk, 2020, Stanczyk et al., 2021) and winnowing (Sahkre et al., 2018; Morgan et al., 2019, 2020, 2021). Additionally, the possibility of dry processing fine coal has arisen with an investigation into numerous techniques and electrostatic and magnetic separation (Dwari and Rao, 2007). Studies relating to pyrolysis and microwave treatment for enhancing coal's magnetic and electro-physical properties have progressed but have not yet reached commercial status (Binner et al., 2014).

Given the lack of a comprehensive review paper on dry separation techniques, understanding the status, development, and challenges is perplexing. Therefore, this paper systematically summarizes the historical development and knowledge of dry coal processing. Processing for coarse, intermediate, fine, and ultrafine particle sizes is distinguished. The impact of operating parameters on separation performance is also studied, and variations of ash content, Ecart Probable Mooyen (EPM) and yield values are provided. The inefficiency of existing dry separation methods is pointed out, and future research needed for dry coal processing is proposed.

2. Dry coal processing techniques

Coal is heterogeneous, consisting of carbonaceous matter (that is burned for energy) and volatile and mineral matter (that forms the impurities) (SACPS, 2015). Beneficiation (or cleaning) is required to remove these contaminants so that the coal meets the requirement. Parameters used to measure the product quality are the calorific value and ash, sulphur, moisture, and fine contents (SACRM, 2011). Two additional parameters determine the effectiveness of a particular beneficiation process: the EPM and the required cut-point density.

The EPM is an index which represents the sharpness with which the coal and impurities are sorted. It provides an indication of the deviation of the distribution curve from a perfect gravity-based separation (Wills and Finch, 2016; Galvin et al., 2018). A lower EPM describes a sharp separation and less particle misplacement while a higher EPM generally represents a low separation accuracy (Kopparthi et al., 2020). The usual EPM for dry coal separators ranges from 0.15 to 0.3 (Pradhan and Mohanta, 2020; Patil and Parekh, 2011) while the water-based processes usually range from 0.02 to 0.025 EPM (De Korte, 2013). The cut-point density (SG_{50}) is the density at which 50 % of the material reports to the heavier (or lighter) fraction in a density concentration. Separations at lower-density cut-points tend to be sharper than separations at higher-density cut-points (Pradhan and Mohanta, 2020). The coal feed quality, market, and adeptness of the selected beneficiation process are the determining factors for successful and profitable coal upgrading (WCI, 2009; SACRM, 2011).

Mineral beneficiation (wet or dry) is comprised of two fundamental operations: liberation and concentration. During the former operation, the valuable coal is released from gangue minerals and then separated in the latter operation (Wills and Napier-Munn, 2008). Separation of the valuable coal from the discarded components is made possible by exploiting some difference in their physical properties in terms of size, shape, density, magnetic predisposition, and electric resistivity (Chen and Wei, 2003; Chen and Yang, 2003; Dwari and Rao, 2007; Patil and Parekh, 2011). Five processing categories can, therefore, be observed: comminution and screening (generally for liberation), sensor-based sorting, gravity-based concentration, magnetic separation, and electrostatic separation. These five categories have advantages and constraints for beneficiating different coal qualities and various particle sizes to yield a desirable coal product at the required capacity efficiently.

2.1. Comminution and screening

Comminution is used to liberate valuable coal constituents from the associated inorganic components, increase surface area for high reactivity, and facilitate the transport of coal particles between unit operations. Comminution is accomplished by crushing in hammer mills and rotary breakers, grinding in ball and pebble mills and screening for particle size classification. These processes rely on differences in hardness and crushability between the coal and gangue counterparts. During comminution, the particles are reduced by five forces: compression, impact, shear and attrition (Asghari et al., 2020; Wills and Finch, 2016). Screening separates the coal into sizes appropriate for further processing by applying gravity and momentum forces through vibration, mechanical agitation and centrifuge (Wills and Finch, 2016).

Perfect particle liberation may not be possible in practice, so the ore is merely reduced to a workable size (Wills and Napier-Munn, 2008). Comminution removes harmful objects, large uncrushable ore, and fine material, thus acting as a pre-process separation stage (SACPS, 2015). Equipment used to treat coal in this aspect are rotary breakers, slate pickers, and scalping screens, all described in the works by SACPS (2015), Mamoodhabadi (2015) and Wills and Napier-Munn (2008). However, These units are implemented for feed ore preparation as they cannot beneficiate coal to the desired specification because they rely on a high degree of liberation at a larger particle size and specific particle shapes.

2.2. Sensor-based sorting

Sensor-based sorting (SBS) encompasses detecting discrete particles and removing those deemed undesired particles. SBS is applied in various industries due to a wide range of detection techniques and currently available powerful computing capabilities (Harbeck and Kroog, 2008). In SBS, particles are mechanically sorted based on certain physical features a sensor identifies. Robben and Wotruba (2019) presented a rundown of SBS development and introduced different applications. Most sensor-based sorters operate similarly, apart from the means of detection, as Manoucherchi (2003) detailed. While focusing on coal beneficiation, the dual-energy x-ray transmission (DE-XRT) sorter is the most applicable. Some investigation into other types, such as the electromagnetic sorter for coal, has commenced, but further evaluation may be required (De Jong et al., 2004); as such, these will not be discussed here.

The DE-XRT sorter has been well-described (Robben et al., 2014; Robben and Wotruba, 2019; Strydom, 2010; Lessard et al., 2014; Zhang et al., 2021; He et al., 2022) and works similarly to the baggage scanning devices at airports. These observe the transmission and attenuation of hard X-rays as they move through a solid medium (Robben et al., 2014). The denser fragments transmit fewer X-rays through the matter (Strydom, 2010; Lessard et al., 2014). These dense components can be told apart from lighter ones based on the relative difference in transmission of the X-rays through the material (Lessard et al., 2014).

Fig. 1 displays the schematic setup of a belt-type DE-XRT sorter. The DE-XRT sorters radiate x-rays over feed ore in arrays at differing relative energies, normalizing any effects of material thickness (Harbeck, 2004; Lessard et al., 2014). The detectors operate as line-scan cameras that register the penetration of the X-rays and convert the information into electrical signals used to create grey-scale X-ray images. The image processing performed by the software allows the use of a colour scale, which shows high-density volumes in yellow, intermediate-density volumes in green, and low-density volumes in blue. A sorting algorithm is applied, and the ejector circuit is employed to separate the desired and undesired particles by a mechanical force, either a burst of

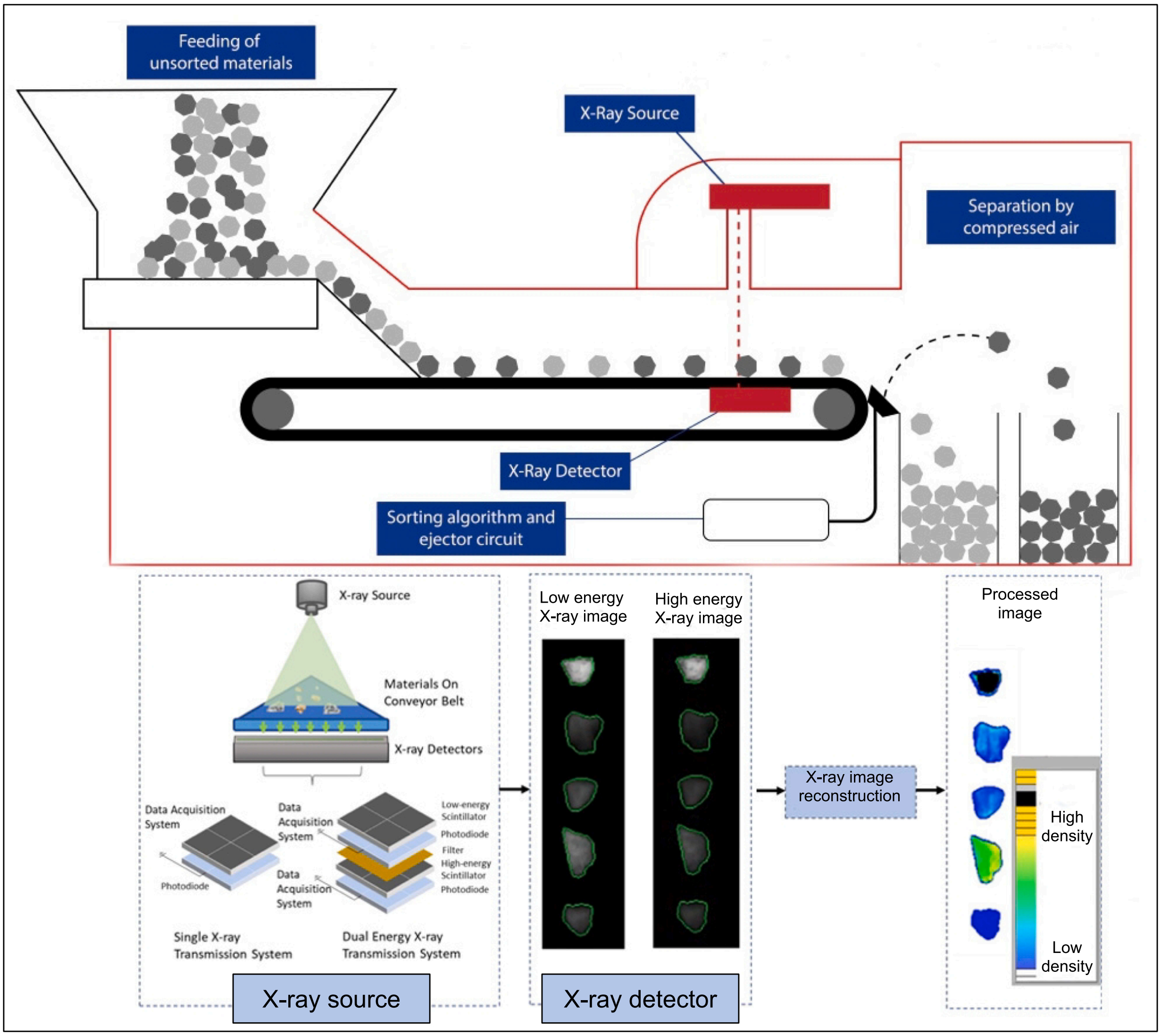


Fig. 1. Schematic of the functioning of a DE-XRT sorter (adapted from SRC, 2021; Zhang, 2016).

air or mechanical flaps and plungers (Manoucherchi, 2003). The operation sensitivity can be varied to either reject or retain more or less unwanted gangue based on some threshold value.

The DE-XRT sorter, being useful as a tool for the concentration of particles, can also be implemented in certain analytical aspects of the washability of individual coal particles (Zhang et al., 2021). Another method available is 3D imaging, such as the novel RhoVol machine developed by De Beer Mining Company (South Africa). It can analyse individual particles by measuring their size, volume and density. The RhoVol uses a rapid mass measurement system and seven cameras at various angles. These cameras capture seven silhouettes of a particle at a given time, and the system develops a 3D model of the said particle by back projecting the silhouettes from different camera views (Fofana and Steyn, 2019). This particle volume model and mass measurement can be used to calculate certain particle properties. The RhoVol is equipped with a sorting functionality to sort a sample based on certain parameters, such as density (Mangera et al., 2016; Botlhoko et al., 2022).

Botlhoko et al. (2022) used the RhoVol as a competitive alternative to the sink-float method. The coal particles (+3–8 mm) were subjected to standard sink-float (1.2–2.1 g/cm3) and RhoVol tests. It was found that the RhoVol could successfully sort coal particles into a broad range of densities, and it can potentially replace the standard sink-float analysis. This study formed the first effort to determine if 3D imaging could separate coal particles based on density and the potential for its application as an industrial process. Further research involving a wide range of coal samples is necessary to determine if 3D imaging is suitable for industrial sorting applications along with an economic analysis.

2.3. *Gravity-based separation*

Observing a significant density disparity between two materials allows for their separation using gravity-based techniques, which are extensively discussed in the literature (Kelly and Spottiswood, 1982; Wills and Napier-Munn, 2008; SACPS, 2015). Variations in the behaviour of particles with different densities within a fluid medium occur due to gravity, centrifugal, and frictional forces. These forces influence the differential movement of particles with varying densities concerning the resistance posed by the viscous medium. Therefore, achieving separation of particles with differing densities is feasible in an appropriate medium (Wills and Napier-Munn, 2008). Additionally, particle attributes (such as size and shape) and medium characteristics (including type, density, and viscosity) further impact the potential and degree of separation in a density-based sorter (Wills and Napier-Munn, 2008; Sahu et al., 2013; Zhao et al., 2015).

Numerous dry coal gravity beneficiation methods have been investigated, such as pneumatic oscillating tables (Patil and Parekh, 2011;

Kademli and Gulsoy, 2013; Chavaldi et al., 2016; Jambal et al., 2020), ADMFB separation (Chen and Wei, 2003; Luo et al., 2007; 2008; He et al., 2016a, b, c; Zhao et al., 2017; Hughes et al., 2017; Langner et al., 2018; Jiang et al., 2019; Fu et al., 2019; Diedericks et al., 2022), air jigging (Weinstein and Snoby, 2007; Sampaio et al., 2020), suction fluidization (Stepanenko, 2016a, Stepanenko, 2016b; Stanczyk, 2020; Stanczyk et al., 2021), winnowing, and reflux classification (Macpherson and Galvin, 2010; Morgan et al., 2019, 2020, 2021; Kopparthi et al., 2020).

2.3.1. Elutriation methods

Air jigging (All-Air jig) and air table variants (Standard Air Table, FGX, KAT and AKA-FLOW) use particle fluidization hindered settling and consolidation trickling. During these methods, particles are subjected to continuous and pulsating airflow, vibration, and inclination to dilate and fluidize particulates (SACPS, 2015; Wills and Napier-Munn, 2008). The forces of momentum, gravity, buoyancy, and friction cause individual particle movement and stratification, where heavier, dense particles migrate to the bottom whilst the light fractions float to the top of the suspension. A given cut-point density determines the point of separation where the heavy and light fractions will be transferred to their respective recovery devices (SACPS, 2015).

Differences between jigging and the various air table designs are attributed to the bed depth, direction of movement of the product and discard fractions and the discharge thereof. Jigs are deep bed separators (Weinstein and Snoby, 2007), whereas air tables are shallow (Chavaldi et al., 2016). Furthermore, several middling fractions can be obtained from the air tables, whereas the jigs can only produce one clean coal fraction and one discard. A co-current flow of product and discard fractions is observed in the All-Air Jig and AKA-FLOW (Dwari and Rao, 2007, Wotruba et al., 2010), whereas the Standard Air Table, FGX and KAT rely on the counter-current flow of the product and discard fractions (Gupta, 2016; Dwari and Rao, 2007; Jambal et al., 2016). Table 1 provides the principle of operation of the air jigs and pneumatic oscillating tables discussed above.

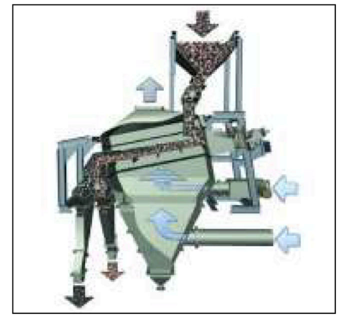
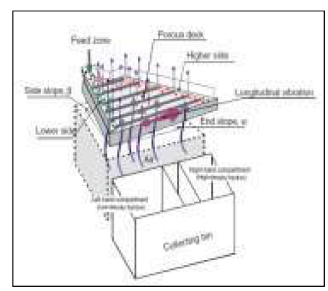
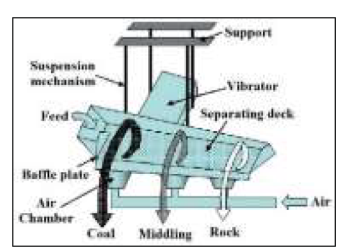
2.3.2. Methods utilizing dry dense medium separation

Particle fluidization and density stratification are also used in dry dense medium separation. Herein, however, a fine and very heavy material is used as a dense medium. This medium is fluidized with air forming a particle suspension with unique pseudo-fluid properties—density and viscosity (Kunii and Levenspiel, 1991). A density stratification of differing-density coal particles occurs once the coal is added to the pseudo-fluid medium (Luo and Chen, 2001). Heavy particles sink into the medium due to forces of gravity and friction, and the lighter particles float due to buoyancy (Firdaus et al., 2012). A dense medium improves fluidisation stability and aids in separation efficiency. However, post-beneficiation requires additional processing to remove the dense medium from the product and clean it for reuse.

A process called the air dense medium fluidized bed (ADMFB), extensively studied in China, was established for coal beneficiation (Luo et al., 2003). The research included the incorporation of vibration into the ADMFB, evaluations of deep and shallow bed separators, enhancements through magnetically stabilized and dual-density beds, and computer-assisted modelling (Chen and Wei, 2005). A commercial ADMFB was introduced in China by the Chinese University of Mining and Technology and Shenzhou Ltd. (Chen and Wei, 2005). The commercial ADMFB is portrayed in Fig. 2, along with an operation schematic.

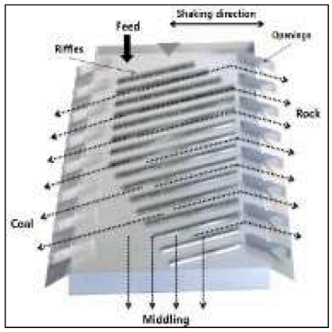
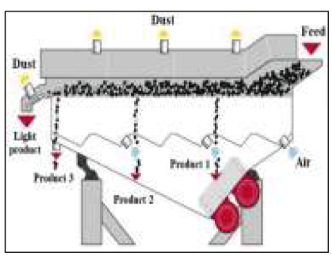
Coal and dense medium are fed into a chamber where air enters upward, fluidizing the dense medium. The heavy discard particles sink onto the tail conveyor, and the lighter coal particles float to the product discharge. Dust collection, correct cleaning, and disposal are also compensated for (Luo and Chen, 2001). The ADMFB uses lower air flow rates and, consequently, less and smaller dust-collecting equipment. It also has minimum moving parts and possibly uses waste heat for

Table 1
A comparison of the principle of operation of various air jigs and air tables (Hughes et al., 2019).

Method	Description	Schematic
All-Air Jig	Ore is fed onto a perforated deck through which air is continuously distributed and pulsated. A stratification of the particles occurs according to size and density as a result of the forces of buoyancy from the air lifting the particle, and gravity and friction pulling it down. Two layers are formed as the particles move along the deck. The discard (heavy) layer forms close to the deck, with the product (light) layer at a certain height above the deck. The discard discharge valve controls the separation cut-point (Weinstein and Snoby, 2007).	 Image source: Weitkaemper and Wotruba, 2010.
Standard Air Table	A particle density stratification is produced by the buoyancy forces of an upward airflow through a porous deck, which is angled and oscillating. Separation is achieved by particles moving in a helical form caused by the momentum of the deck oscillation. Moments of inertia and traction force the heavier particles towards the higher end of the table. Gravity and buoyancy aid the light and slightly fluidised particles over the denser bed and towards the lower section of the deck (Dwari and Rao, 2007; Chavaldi et al., 2016; Gupta, 2016).	 Image source: adapted from Doodibah *et al.*, 2002.
FGX air table	The FGX integrates the design and operation of a standard air table with an autogenous medium. The airflow is designed to fluidize and convey fine, dense material such as magnetite or coal. This creates an autogenous particle bed suspension with unique fluid-like	 Image source: Zhang et al., 2011.

(*continued on next page*)

Table 1 (*continued*)

Method	Description	Schematic
	properties, aiding the lighter particles to float (Ghosh, 2013).	
KAT air table	The KAT employs airflow and vibration on a flat perforated deck featuring slanted riffles and block plates on opposing sides. Due to gravity, friction and momentum, heavier material settles and travels in the direction of vibration, while lighter material floats and shifts towards the opposite direction due to buoyancy. Material accumulates against the block plates until it reaches an overflow point. The intermediate material progresses through the table and is discharged at the lower end (Jambal et al., 2016).	 Image source: Jambal et al., 2016.
AKA-FLOW air table	Coal is introduced onto a flat screen within three successive air chambers. The particles are fluidized through buoyancy and momentum by a blend of vibration and airflow. Vibrations aid particle movement along the channels, resulting in material segregation. Heavier waste material, sinking to the bottom of the plate due to gravity, is released after each chamber. In contrast, the clean coal fraction and intermediate material floating due to buoyancy are extracted at the channel's terminus (Wotruba et al., 2010).	 Image source: CES, 2024.

simultaneous coal drying. These are some advantages of the other dry processing techniques (Azimi et al., 2013). The applicability of the ADMFB for the South African coal market has been investigated by Hughes et al., 2017; Langner et al., 2018; and Diedericks et al., 2022.

2.3.3. *Negative pressure pneumatic separator*

A particle can be fluidized using a suction force stronger than the effects of gravity and friction acting on the particle. This separation technique uses a vacuum created by a nozzle of a specific design, which is located above a layer of particles. The particles are thus set into motion and fluidized by the force of suction. The SEP-AIR unit introduced by Gormash Export in Novosibirsk, Russia (portrayed in Fig. 3) is based on this principle (Stepanenko, 2016a; Stepanenko, 2016b).

In this unit, the fine fraction is eliminated by a perforated screen. Coal particles remaining on the screen are transported beneath the suction nozzle. The nozzle comprises a fluidization and vortex chamber wherein the particles are exposed to an upward airflow. The force of suction causes the lighter particles to lift into the fluidization chamber through the vortex chamber, where centrifugal forces transport the particles collected as a product. The heavier particles are not affected by the suction force and remain on the conveyor until discharged at the end (Stepanenko, 2016a; Stepanenko, 2016b).

The density at which separation occurs is specified by the hydraulic size of the particles forming a layer on the conveyor, which in turn is set by the speed of the gas phase passing through the fluidized layer. Cyclones and filters are used to treat any dust that is generated (Stepanenko, 2016a; Stepanenko, 2016b). In the SEP-AIR process, each particle experiences a double separation, first a fluidization and second a vortex capture. This contrasts the traditional means of fluidization and the reason such a high yield is attributed to this process (Stepanenko, 2016a; Stepanenko, 2016b). Moreover, former pneumatic separators tried to copy the operating principles of water-based separators. Many unit inefficiencies will be observed without considering any changes in the properties of the air medium (Stepanenko, 2016a; Stepanenko, 2016b). A commercial SEP-AIR plant was commissioned in Kuzbass at the Bungursk coal mine in Russia and can produce up to 12 different density products. The SEP-AIR process can also be classified according to particle size and shape.

Another design pertaining to the negative pressure pneumatic separators was provided by Stanczyk, (2020). In this unit, the particles are transferred onto a perforated rotary cylinder consisting of upward-facing air nozzles and an auxiliary blower. This design generates an overpressure underneath the layer of particles. It works together with the curve of the cylinder to initiate particle vibrations and displacement and thereby increase the productivity of the sorting process. This also allows for particle drying and reduction in any particle sticking because of moisture. A suction nozzle, connected to a fan, is located above the rotary cylinder where particles are lifted by suction into a separator, which removes them from the air stream and leads them into a reservoir. The particles that do not succumb to the suction force slide from the cylinder. The general idea of how the NPPS system works and a semi-industrial separator are presented in Fig. 4 (Stanczyk et al., 2021).

2.3.4. *Methods under investigation*

Winnowing (Liu, 2009; Sinha et al., 2016; Sakhre et al., 2018; Morgan et al., 2019, 2020, 2021) and dry reflux classification (Galvin, 2004; Laskovski et al., 2006; Macpherson and Galvin, 2010; Kopparthi et al., 2020) currently show promise in developmental stages with coarse and finer coal fractions, respectively. However, a deeper investigation and possible upscaling to provide a more realistic idea of the capabilities are still required.

The fundamental principle of winnowing involves using wind to displace lighter material by forces of momentum and buoyancy, leaving heavier material behind due to gravity. This system employs horizontal airflow where lighter particles are propelled into the collection chute while denser particles, more influenced by gravity, descend into the heavy fraction bin. Winnowing can yield multiple products varying in size and density (Sinha et al., 2016; Sakhre et al., 2018).

Reflux classification (RC) has been proven effective in water-based fine particle separation. Therefore, some studies have tried to determine if it applies to processing in the dry fine coal fractions. Some research into the performance of RC has progressed on this subject on a laboratory and commercial scale (Galvin et al., 2002; Galvin, 2004; Doroodchi et al., 2006; Laskovski et al., 2006; Macpherson and Galvin, 2010a). The RC makes use of a section made up of parallel inclined channels that are placed above a conventional fluidized bed (Galvin, 2004). Air is injected (at a given velocity) into the fluidized bed, and coal is added at the top to fluidize. The fine and light particles move into the inclined channels and exit at the top. If the particles are too dense or large, they will sediment onto the channel walls and return to the

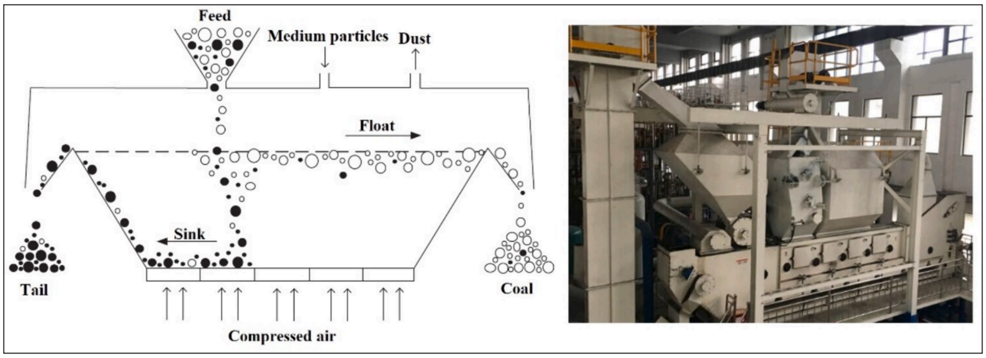


Fig. 2. Schematic (left) and picture (right) of an ADMFB separator (adapted from Fu et al., 2019).

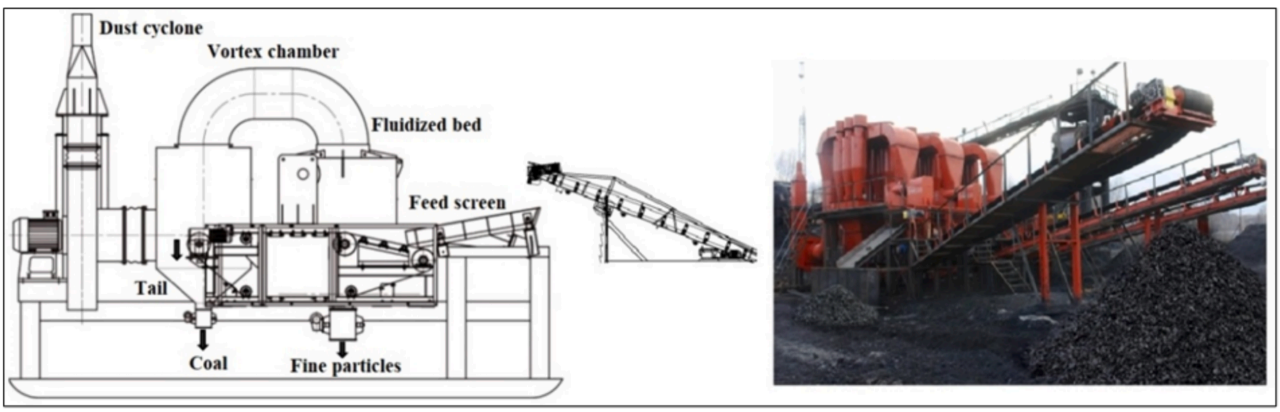


Fig. 3. The SEP-AIR pneumatic separator (from Gormash Export, 2016b).

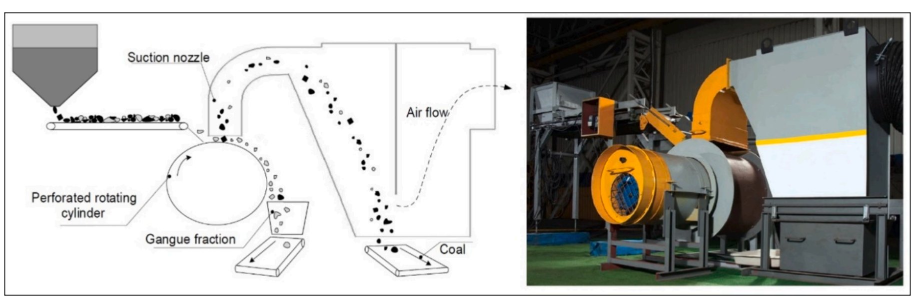


Fig. 4. Schematic of an NPPS (left) and a semi-industrial NPPS (right) (Stanczyk et al., 2021).

fluidizing channel. The heavy material ultimately discharges at the bottom. Due to the increased vessel area arising from the incline channels, the RC allows higher throughputs than the traditional fluidized bed (Callen et al., 2007).

The separation within the vertical fluidization section relies on mechanisms of hindered settling, which is affected by particle terminal velocity (closely related to size). The use of the inclined section overcomes the inefficiency of the fluidizing section, where the similar movement of heavier particles that are fine and lighter particles that are large (having the same terminal velocity) is compensated for. This section induces a re-suspension of particles to ensure that light particles move to the overflow. Heavier particles settle on the inclined plates and re-enter the fluidized bed section. This process fluidizes them once more and returns them to the inclined plates for potential secondary separation before moving to the underflow (Laskovski et al., 2006; Macpherson and Galvin, 2010a). An accumulation of fine and dense particles in the mixing zone generates an autogenous dense medium that helps the coarse light particles move directly to the overflow (Das and Sarkar, 2018). One disadvantage of an air-fluidized RC is that the separation happens based on size rather than density (Callen et al., 2007). Fig. 5 portrays the schematics of a winnower and reflux classifier.

2.4. Magnetic separation

The valuable content of coal is diamagnetic and mineral matter could be diamagnetic or paramagnetic. Therefore, it is possible to process using high-intensity magnetic separation where the mineral matter associated with coal is paramagnetic such as pyrite (Van Driel et al., 1984). An important phase in the dry separation of coal is the desulfurization process, where pyrite-bearing minerals are removed to prevent the formation of sulphur oxides during coal combustion. Techniques most applicable to coal are the rare-earth-roll-magnetic-separators (RERMS) which provide stronger magnetic forces, have higher capacities, lower power consumption and are available and affordable when compared to other magnetic techniques (Elder. 2003, Order et al., 2003; Tripathy et al., 2017; Chen et al., 2019).

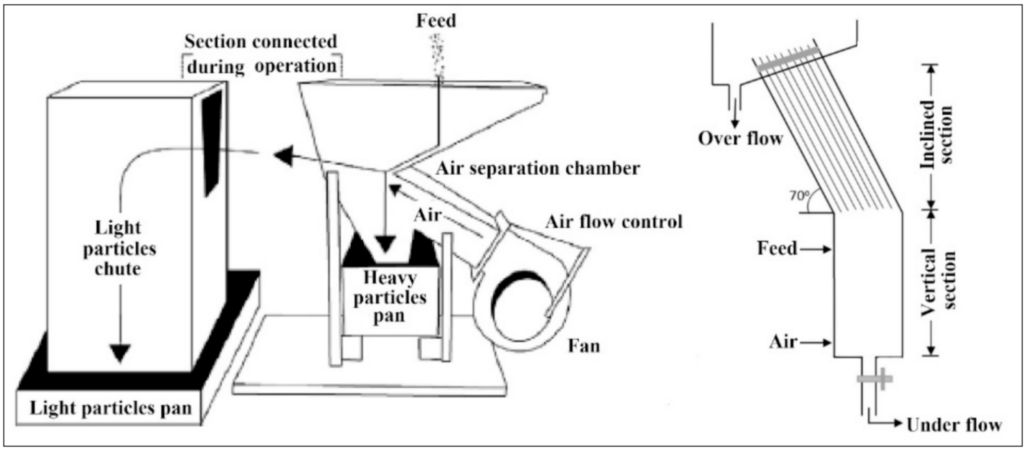


Fig. 5. Schematics of a Winnower (left) (Liu, 2009) and Reflux Classifier (right) (Kopparthi et al., 2020).

The RERMS comprises a magnetic roll and an idler roll covered by a thin conveyor belt made of non-stick Kevlar or glass Teflon. The magnetic roll comprises disk-shaped permanent magnets within mild steel rings (Tripathy et al., 2017). Coal particles are fed onto the belt and transported across the magnetic roll, encountering the magnetic field. Paramagnetic materials, those attracted to the magnetic roll, adhere to the belt's surface and are released upon the roller's rotation away from the magnetic field. Diamagnetic particles, unaffected by the magnetic field, separate from the conveyor. The system includes splitters and collection hoppers at the belt end to redirect and gather different particles, facilitating their separation (Elder, 2003; Tripathy et al., 2017). Fig. 6 illustrates the operational principle of the RERMS.

2.5. *Electrostatic separation*

Electrostatic separation can be used for separation of coal from gangue minerals (Wills and Napier-Munn, 2008; Dance and Morrison, 1992). Tribo-electrification seems to be the most viable since it is suitable for ultra-fine materials (smaller than 75 μm) and minerals with similar electro-physical properties (Kelly and Spottiswood, 1989; Manouchehri et al., 2000; Dwari and Rao, 2008).

The tribo-electrostatic (TBS) system involves a tribo-charging zone and a subsequent separation zone. Particles undergo differential charging in the former and subsequent physical separation in the latter. This system includes a feeder, free fall separator, two adjustable electrode plates, collection bins, and a high voltage direct current (DC) source (Mohanta et al., 2016). Numerous studies have delved into

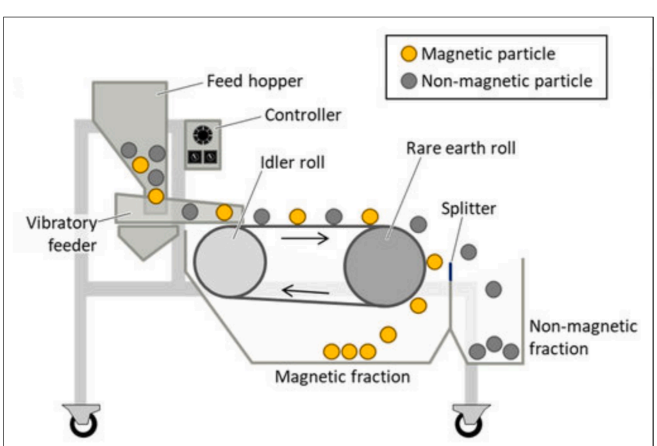


Fig. 6. Schematic of the operating principle of the RERMS (Park et al., 2021).

aspects of the TBS process, including tribo-charging characteristics, methods, and configurations of the separation unit (Mukherjee et al., 1987; Ban et al., 1993; Higashiyama and Asana, 1998; Trigwell et al., 2003; Dwari and Rao, 2008; Dwari and Rao, 2009; Bada, 2010; Zhang et al., 2016; Wang et al., 2017).

During tribo-charging, the particles are charged by contact friction against other particles or a container wall, such as in a rotary tube (Dwari and Rao, 2007). The work functions of the surfaces in consideration determine the magnitude of the charge and its polarity (Mohanta et al., 2016). During the subsequent separation, the charged particles are allowed to fall through an electric field generated by the electrode plates and are deflected according to the magnitude and polarity of their charges. Literature shows that clean coal will take on a positive charge while ash-forming minerals charge negatively (Lockhart, 1984; Tao et al., 2008).

The rotary triboelectrification separator (RTS) is characteristic of a copper-covered rotary wheel which charges materials through friction movement. Copper is used for the friction wheel because it provides an optimal work function (falling in between the minerals and macerals) (Dwari and Rao, 2006). Fig. 7 shows a schematic of an RTS. This system has been successful for several materials, including coal (Bada et al., 2010; Tao et al., 2011).

3. Applicability and limitations of the various dry processing techniques

All the separation methods described above have merit for dry coal processing, but their applicability and any associated limitations must be considered. This includes the following factors: coal type and densimetric properties, particle size range, capacity, moisture content, feed preparation and feed presentation.

3.1. *Coal type and densimetric properties*

Some dry processing techniques may be more suited to specific applications because of feed coal quality and the operating principle and capabilities of the separator. A distinction should be made between de-stoning and concentration. Most dry beneficiation methods can be successfully used in de-stoning, pre-concentration, and salvage because of the ease of separation of the extremely poor-quality shale from coal, as well as the generally larger particle sizes involved (Wotruba, 2006; Weinstein and Snoby, 2007; Tripathy et al., 2017). Preparing coal particles prior to processing offers opportunities to enhance mine productivity and profitability. Initially, it reduces the volume of material requiring downstream crushing, screening, and processing, consequently diminishing the waste handled by the coal washing plant and discarded in tailings ponds post-processing. Moreover, by reducing both

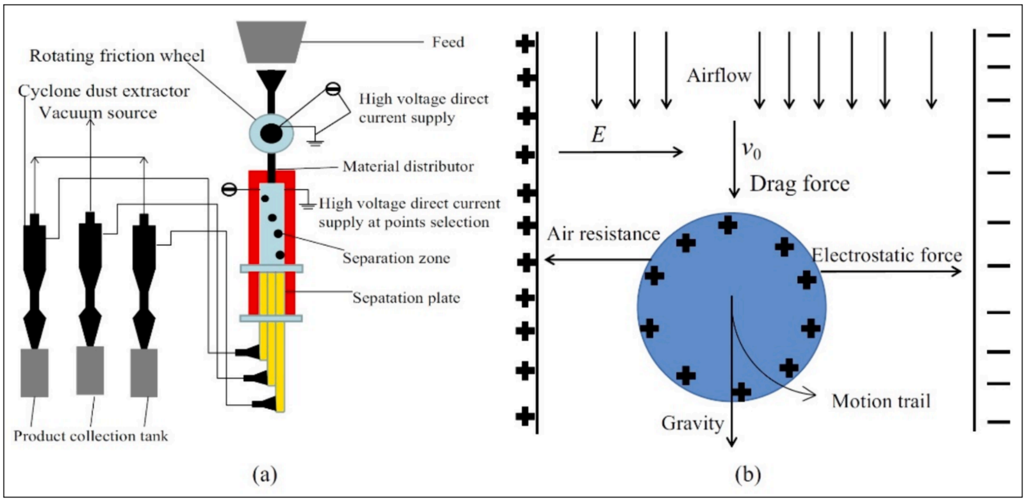


Fig. 7. The draft of triboelectrification separation system (Yushuai *et al.*, 2021).

waste material and water usage during processing, it contributes to a decrease in tailings dam size and water demands, thereby lowering the overall operational costs (Lessard et al., 2014; Lessard et al., 2016; Wills and Finch, 2016; Revuelta, 2018).

When beneficiating to a clean coal product, dry processing is appropriate for materials where near-dense material is minimal or in cases where a significant upgrade in coal quality is not required to meet specifications (De Korte, 2013). The portion of material that is present in an ± 2 EPM density range is defined as near-dense material (De Korte, 2013). Near-dense material can complicate a process by causing increased particle misplacement, lower yields, and less control of the product quality (De Korte, 2013). This is particularly true for gravity-based separation techniques. In a study conducted by (Jambal et al., 2017), where the middling characteristics were found to be nearly identical to the feed, it proved necessary to keep the middling amount as low as possible. In plant operations, the middlings produced (±20 %) may need to be recycled into the feed for further recovery. When considering a DE-XRT sorter, it is possible to overcome issues pertaining to near-dense material by implementing stricter selectivity, which may, however, significantly affect throughput and production (Von Ketelhodt and Bergmann, 2010). Due to the capabilities of DE-XRT to detect other particle and material properties, sorting can also be utilized for desulphurization, separation of the density similar torbanite from coal and size, shape, and washability classification (Von Ketelhodt and Bergmann, 2010; Zhang et al., 2021). This is also true for the novel RhoVol 3D imaging process. In gravity-based separation, pyrite inadvertently coincides with the heavy material due to its higher density and is, in so, removed (Sampaio et al., 2008; Weinstein and Snoby, 2007). Density separations are quite reliant on mass and surface area, and therefore, some of these techniques can also be utilized for size and shape classifications (A.I. Stepanenko, CEO Gormash Export, personal communication, September 2019).

The presence of near-dense material does not severely affect the magnetic and electrostatic processes. This is because these processes do not rely on density, and the required fine grain size is associated with a high degree of liberation. These techniques are, however, mostly applicable to pyrite-bearing coals and used in desulphurization applications. This is because pyrite possesses significantly differing magnetic and electro-physical properties compared to the carbon and other mineral matter in coal (Van Driel et al., 1984; Ciccu et al., 1991). It is, however, still possible to separate other medium and weakly magnetic material in the RERMS depending on magnet strength (Tripathy et al., 2017). Similarly, separation of small amounts of conductive from large amounts of non-conductive material and concentration of materials of differing electro-physical properties is also possible in TBS (Kelly and Spottiswood, 1989). Some studies show that treating a coal sample with heat can improve the magnetic and electric properties making it easier to separate them with RERMS and TBS. Examples of these are pyrolysis and microwave pre-treatments. These treatments also show potential in dewatering applications and improving grindability (Binner et al., 2014).

The possibility of using TBS to separate different coal macerals has also been investigated, and several techniques have been reported by different researchers (Nag et al., 2021). Vitrinite and inertinite have different oil production rates. Vitrinite proves better because of stronger fluidity and decomposition reaction (Jin et al., 2014). The electrification ability of vitrinite differs from that of inertinite; the former charges positively while the latter takes on a negative charge. (He et al., 2018). Yushuai *et al.* (2021) separated the macerals of low-rank coal by TBS. In comparison to the other maceral separation techniques, TBS has significant advantages. Zhang et al. (2022) implemented permittivity and charge–mass ratio measuring systems to analyse vitrinite and inertinite charging properties under several modified conditions.

3.2. Particle size, cost and capacity

Proper particle-size distribution (PSD) before separation is important not only for handleability but also for the feed particle size, especially the top and bottom size, which is often a limiting factor in the applicability of a specific method. In general, in most dry separators, the separation efficiency significantly deteriorates for particles smaller than 6 mm (Patil and Parekh, 2011). Moreover, efficient dry processing can be achieved at PSD ratios between 2:1 and 4:1 (Jambal et al., 2020). This is proven by the theory of equal settling particles developed by Rittenger in 1867 as explained in the work by Patil and Parekh (2011).

The All-Air Jig and ADMFB can process feed with a large PSD ratio (10:1) (Weinstein and Snoby, 2007). Dense medium, vibration and oscillating motion can assist in stratification and efficient separation of possibly wider size ranges (Patil and Parekh, 2011). Particles falling outside of the operating ratio range may be misplaced. A narrow particle size range is imperative for most dry processes. Table 2 lists the PSD data for the techniques considered in this paper.

When considering a size benchmark of 6 mm to distinguish between fine and coarse coal, the gravity-based processes such as the DE-XRT sorter, All-Air Jig, air table, FGX, ADMFB, SEP-AIR and winnowing methods are suitable for processing larger PSD ranges. All these methods can process coal at relatively large capacities, but the cost differs depending on the method type. The DE-XRT sorter proves costly at higher operating capacity owing to the requirement of proper x-ray detection and residence times. The FGX, All-Air Jig and air tables are

Table 2
Particle size distribution and capacity ranges for the dry processing techniques.

Dry processing technique	Particle size distribution (mm)	Capacity (tph)	Reference
DE-XRT	10–120	70–240	King, 2015
All Air Jig	0.5–50	50–120	Weinstein and Snoby, 2007
Air table (fine)	0–6	0–5	Chalavadi et al., 2016; Patil and Parekh, 2011; Gupta, 2016
Air table (coarse)	6–75	300–1200	Patil and Parekh, 2011; Honaker, 2008; Stotts et al., 1987
FGX	6–80	10–350	De Korte, 2013; Dwari and Rao, 2007; Zhang et al., 2011
KAT	1–10	100	Jambal et al., 2016
AKA-FLOW	0.045–3	5–25	Wotruba et al., 2010
ADMFB	6–300	150	Dwari and Rao, 2007; Sahu et al., 2009; Chen and Wei, 2003
Modified ADMFB	0–6	0.15–8	Dwari and Rao, 2007; Hughes et al., 2017
SEP-AIR	1–100	45–200	Gormash Export, 2016
Dry reflux classifier	0.2–8	300 gr/min	Macpherson et al., 2011
Winnower	6–100	0.006–0.01	Sahkre et al., 2018
RERMS	0.075–25	2–10	Tripathy et al., 2017
TBS	0–1	0.012	Mohanta et al., 2016; Dwari et al., 2015

low-cost options at higher capacities but may suffer from separation inefficiency. The SEP-AIR and NPPS units perform well and at high throughputs. The ADMFB is considered a high-cost process due to the dense medium removal post-processing. These methods are also capable of processing finer coal, but most of this work is at an early developmental stage (Chen and Wei, 2005; Macpherson et al., 2011). Moreover, some of the processes are not practical at smaller particle sizes due to the reduction in processing capacity. This is especially true for the DE-XRT sorter (King, 2015; Strauss, 2016; Wotruba, 2006; von Ketelhodt and Bergmann, 2010).

Inefficient fine particle recovery using conventional gravity separators is a recognized challenge (Majumder et al., 2003). Due to the small mass and high surface area of a fine particle, low particle momentum, hypercoagulation, difficulty in overcoming the interparticle energy barrier, low settling rates and high viscosity are observed (Sivamohan, 1990; Amariei et al., 2014). As the particle size reduces, the difference between the settling velocities of heavy and light particles decreases, and the performance of gravity separation becomes weak (Das and Sarkar, 2018). When particles are ultra-fine, the settling kinetics are slow. Thus, even though the density criterion is favourable for these particles, the time needed for efficient separation is impossibly long.

Traditional gravity separators are not able to provide such long residence times and are, making them impractical for fine particles. As a result, sorting fine particles at high throughput poses challenges. However, finer particle sizes often result in increased mineral liberation, necessitating these liberated valuable particles' economical and rapid separation. Advanced gravity separators must address this technological gap to enable cost-effective and swift separation of fine minerals, paving the way for their commercial viability in fine coal cleaning applications.

Extracting the fine undersized material is crucial not only to mitigate particle misplacement, as previously discussed but also to decrease the fraction of dust particles requiring treatment in the dust-handling system (De Korte, 2013). Systems like the FGX and ADMFB utilize an autogenous or dual-density medium. Presence of fine material in the feed aids in an improved medium particle suspension (Ghosh, 2013). The number of fine particles present needs to be controlled to below 10 $\%_{wt}$ so that the stability and properties of the suspension are not altered (He *et al.*, 2016). Moreover, fine removal also prevents particle sticking and equipment plugging where moisture is present (De Korte, 2014).

The standard air table, AKA-FLOW and KAT separators are available and for the fine coal particle size ranges. The RERMS and TBS methods find most use in fine and ultrafine coal processing (<1mm). Most dry magnetic separators are suitable treating coal larger than 75 μm whereas the TBS is comfortable with processing coal particles as fine as 45 μm (Trigwell et al., 2003b; Tripathy et al., 2017; Mohanta et al., 2016; Dwari et al., 2015).

The fact that particles that fall outside the allowable operating PSD range could lead to displacement has already been mentioned. This may be because of dilution, liberation, mineral exposure, detection, ejection force and trajectory issues. A similar particle misplacement phenomenon is observed in processing with RERMS and TBS but concerning magnetism and electric charge, respectively. The effects of PSD on separation efficiency in RERMS separators have been extensively studied. The overlapping trajectories of large, weakly attracted particles with small non-magnetic particles in a magnetic field were found to be an issue (Gehauf, 2004; Tripathy et al., 2017; Ibrahim et al., 2017). Particle size also influences charging and separation in TBS (Kelly and Spottiswood, 1989). Larger particles obtain a lower charge than that of a smaller particle. Therefore, displacement of large and conducting particles into the non-conducting material may be observed because of a weaker attraction in the electric field. Similarly, the fine conducting material may be contaminated with small non-conducting particles since small particles are more readily influenced by surface charge (Wills and Napier-Munn, 2008; Kelly and Spottiswood, 1989).

3.3. Moisture

The moisture content of the feed proves important in dry processing. Processes such as the DE-XRT, air jig, air table, SEP-AIR, NPPS and coal winnower can operate in the presence of moisture provided that the amount of fine material is limited and the particles can free-flow without plugging the material handling systems (De Jong et al., 2004; Weinstein and Snoby, 2007; Von Ketelhodt and Bergmann, 2010; De Korte, 2014; Gupta, 2016). Therefore, there is not always a need for extensive drying before processing.

Typical coal surface moistures for the air table, air jig and SEP-AIR range between 3–7 % (Stotts, 1987; Gupta, 2016; Weinstein and Snoby, 2007). While the NPPS can process coal in the moisture range of 12–20 % (Stanczyk et al., 2021). Particle surface adhesion and agglomeration cause particle misplacement due to entrainment and misdetection (Weinstein and Snoby, 2007). This is observed in the FGX, where a portion of the fine coal is used as an autogenous fluidized bed (De Korte, 2014). Kademli *et al.* (2021) examined the influence of moisture (7–25 %) on the FGX separator performance. The findings indicated a notable impact of moisture content on separation efficiency. As moisture content increased, both separation efficiency and EPM values showed an inverse relationship, with optimal outcomes observed at minimal moisture levels. Xia et al. (2015) investigated the utilization of hot gas in drying and cleaning processes, concluding that the amalgamation of dewatering and separation holds promise for cleaning low-rank coals like lignite and others within this range.

In separators where a dense medium such as magnetite is used (ADMFB, DRC), similar adhesion of the medium particles to each other, the coal and vessel walls are observed in the presence of moisture. As a result, a portion of the magnetite powder agglomerates, the contact efficiency between air and particle reduces, nonuniformity in bed density increases, and the particle dispersion decreases. Moisture contents ranging from 3–4 % are necessary in these cases (Sahu et al., 2009; He et al., 2015). Luo et al. (2010) suggest a method for increasing the surface hydrophobicity of the magnetite particles (using stearic acid as the modifying agent) to control the moisture content to less than 2 %. It proves an effective technique for increasing gas–solid fluidized bed applicability to dry beneficiation of feedstocks with different external moisture contents.

The RERMS and TBS processes are primarily used for dry mineral processing. Some investigations of the RERMS conducted on a wet basis have been done by Rylatt and Popplewell (1999). Even so, suitable moisture content during RERMS processing only requires that particles do not adhere to each other and the machine (Mineral Technologies, 2018). TBS is only concerned with particles that are bone dry. Some studies have attempted to use a medium other than air (such as a dielectric liquid) (Wills and Napier-Munn, 2008; Kelly and Spottsiwood, 1989). Moisture, temperature, and relative humidity are important parameters during the charging of particles (Cruise et al., 2022).

3.4. Additional feed preparation

Feed preparation includes comminution, screening for the removal of undersized material, drying to ensure a suitable moisture content and particle surface cleaning or de-sliming. The importance of crushing and the control of the amount of fine material and moisture contents in the feed has already been discussed. Additionally, removal of any minute particulate contaminants that are present on the particle surface, may be necessary. This is particularly true for cases where the separation mechanism depends on surface characteristics such as the RERMS and TBS processes. For these, the particle surfaces must be free of organic materials and dust as this may affect the magnetic susceptibility, charge formation, and dissipation, respectively (Fraas, 1962).

3.5. Feed presentation

How the feed ore is presented to the separator plays a role in some processes. A monolayer of particles presented at the correct particle speed is required for belt-driven operations such as the DE-XRT and RERMS (Strauss, 2016; Tripathy et al., 2017). However, the orientation of the particle is inconsequential in DE-XRT sorting as the entire mass of the stone is detectable, and the dual-energy sensor array negates the effects of geometry (Strydom, 2010; Lessard et al., 2014). The RERMS is, on the other hand, affected by particle orientation and may require the magnetic portion of a coal particle to be exposed to the magnetic roll. The feed to the SEP-AIR unit is also belt driven but only requires a particle monolayer when processing feed with a large particle size ratio and works optimally when processing a multi-layer feed with a small particle size ratio (A.I. Stepanenko, CEO Gormash Export, personal communication, September 2019). The coal winnower, utilizing a single-line particle flow, may also be affected by particle speed and orientation. If the proper flow of the feed is maintained, particle orientation should not affect most other dry-density separations (Weinstein and Snoby, 2007).

Feed rates in the air table variants prove important to ensure readily fluidized particles. Feed flow rates that are too high can cause a thick particle bed that cannot fluidize effectively. On the other hand, feed rates that are too low lead to inadequate bed formation (Chalavadi et al., 2016; Patil and Parekh, 2011). Similar results were obtained in a study by Jambal et al. (2017) investigating the feed flow rates in a KAT separator. At low rates, a stable, dense medium suspension is not achieved, and middling yield increases due to the misplaced heavy light fractions. Ample dense material during operation forms a stable dense layer suspension on the deck, obtained at increased coal feed rates. Additionally, the kinetic energy of the feed flow forces the separation to the lower deck portions, which allows for efficient reduction of the middling fractions. However, high feed rates reduce the residence time causing poor stratification and possible back-mixing.

The feeding position in an ADMFB affects the movement of coal particles. The impact of the feed height on the fluidization characteristics was studied by Jiang et al. (2019). Efficient separation was achieved when the material was introduced into the ADMFB from the upper or middle sections. Conversely, poor separation efficiency was observed when particles were fed from the bottom due to the inability of low-density particles to float to the upper layer of the fluidized bed. Initial fluidization of dense medium is required before introducing coal particles in processes such as the ADMFB and DRC. Ineffective separation could be attributed to improper presentation of the particles to the process (Wotruba, 2006; Kelly and Spottiswood, 1989).

3.6. Operating parameters

Some studies have focused on investigating the effects of certain operating parameters on separation efficiency. Regarding the air table separator, operating variables such as vibration frequency, table inclination, feeding speed rate and baffle properties were proven to directly impact separation efficiency (Chavaldi et al., 2016; Patil and Parekh, 2011). A proper residence time is essential for acceptable separation. Similar results were obtained for a study on the effects of airflow rate, cross-table inclination, and vibration frequencies in a KAT separator (Jambal et al., 2017). The effects of the vibration amplitude, frequency, and vibration direction angle, longitudinal deck angle, feeder frequency and baffle plate height on the FGX were proven imperative in studies by Zhang et al. (2011) and Yu et al. (2016).

Factors that influence the fluidization quality in the ADMFB include the air distributor, the fluidised bed's geometry, the dense medium's characteristics, and the air velocity. Among these factors, air velocity seems more important for attaining optimal separation as it significantly affects fluidization characteristics and the behaviour of bubbles and particles. Adequate loosening of the material is the premise of the stratification based on density to obtain an effective separation (Jiang et al., 2019). It is essential to avoid excessive bubbling or turbulence, which results in the back mixing in ADMFB. Investigation of the fluidized bed stability was done by Zhang et al. (2020), wherein the effects of gas velocity on density distribution were analysed. At lower velocities, the small bubble sizes proved unsuitable for fine particle processing. As the gas velocity increases, so does the bubble size, which negatively affects the bed stability, causing increased density fluctuations. Yang et al., 2013 described that the mixing and stratification in an ADMFB mainly depend on the bubbles. Thus, bubble characteristics such as size and rise velocity significantly affect the separation performance. Small bubbles create a drag force that is sufficient to lift light coal particles to the top of the bed. The force of gravity supersedes the drag force, meaning that the movement of the heavier particles remains unaffected. Appropriate gas velocity improves density stratification leading to a higher separation efficiency (Diedericks et al., 2022).

Additionally, as the bed height increases, the bubbles become larger. However, bed heights that are too low do does not provide adequate space for proper particle segregation. At increased bed heights, the rising distance of the bubbles increased, weakening their activity and enhancing back mixing and aggregation. Thus, the static bed height should be maintained in the appropriate range (He et al., 2016b). Fu et al. (2019) revealed that ADMFB performance is not sensitive to the excess gas velocity allowing for comparatively wide airflows during operation. Choung et al. (2006) investigated the separation efficiency of ADMFB with variations in operating parameters, including air speed and particle size (coal and medium). Enhancing the separation efficiency of the ADMFB process for fine coal involves employing a smaller medium size, thereby creating a more stable fluidized bed with moderate airflow. However, when utilizing magnetite particles smaller than 45 μm, the fluidized bed became excessively viscous, resulting in poor separation. Azimi et al. (2017) used response surface methodology to investigate the effects of superficial air velocity, residence time and bed height on the performance of the ADMFB separator. Other investigations emphasized the impact of superficial gas velocity and the coal-to-magnetite weight ratio on the separation efficiency of the ADMFB (Mohanta et al., 2011, 2015; Hughes et al., 2017; Diedericks et al., 2022). Findings indicated that product ash was more reliant on the superficial gas velocity than the coal-to-magnetite weight ratio. Sahu et al., (2011,2013) also conducted a study focusing on the stability characteristics of various fluidized bed shapes. The geometry of the fluidized bed column cross-section notably impacts the bed's stability. Specifically, the rectangular cross-sectional shape exhibits superior stability properties when compared to square or circular shapes.

Operating parameters proving important for the negative pressure particle separation type units include the flow patterns and speed of the air produced by the main fan, particle behavior in the fluidization section, feed layer thickness and residence time (Stepanencko, 2016a; Stepanenko, 2016b; Stanczyk et al., 2021).

The variables affecting the RERMS include feed rate, roller speed, splitter position (Fujita et al., 1981; Hucko and Maronde, 1982; Van Driel and de Kerk, 1983; Male, 1984). Dwari and Rao (2009) established that the time for tribo-charging, voltage, airflow, and fluidization residence time may affect the separation efficiency.

4. Performance

The performance and success of a particular dry coal beneficiation process varies and depends heavily on the process application and limitations (as described). EPM, cut-point density, reduction in ash value, and product yield can be used to determine the efficiency of a certain process. The following sections discuss these for each process.

4.1. Sensor-based sorting

Typical performance data available for a DE-XRT sorter is provided in Table 3. These results are supported by De Korte (2013), Robben et al. (2014) and Von Ketelhodt and Bergmann (2010). As mentioned, stricter thresholds can produce higher efficiencies at the expense of throughput. Table 3 shows a significant decrease in ash content and an improvement in the calorific values of the product by using DE-XRT. This sorter has the potential to become an integral component of future dry coal cleaning plants but may not be capable of delivering a product quality at a capacity that competes with a wet beneficiation plant unless operating numerous machines with re-processing.

4.2. Gravity-based separation

Table 4 summarises published performance data for the established gravity-based separation units regarding the EPM, yields, ash value, and cut-point density. The data for each method are further discussed in the sections that follow.

The following sections provide further context for the performance data relating to gravity-based beneficiation techniques as provided in Table 4 above.

4.2.1. Air jig

Most of the jigging applications for dry coal processing are in the coarse coal circuit. Herein, an air jig can provide separation efficiencies ranging from 0.16 to 0.21 but at quite a high cut-point density (2.0–2.2 SG) (Weinsten and Snoby, 2007). The ash value data shows a larger difference in the discard from the feed than from the product, which indicates that the separation is predominantly de-stoning. Charan et al. (2011) used the All-Air jig manufactured by Allmineral in Germany to beneficiate Indian high-ash non-coking coals. At a capacity of 50 t/h coal (+5–40 mm) with an ash content of 40 % produced a concentrate with an ash content of 33 %.

For the fine coal fractions, some studies have been conducted. Boylu et al. (2013) investigated air jigging of three coal samples in the minus 4 mm size range. The ash value reduction from feed to concentrate for the first, second and third samples was 31.75 % to 25.57 %, 33.64 % to 19.59 % and 37.28 % to 24.24 %, respectively. This coincides with 60.5 %, 51.2 % and 62.3 % yields.

Sampaio et al. (2008) used dry jigging for the desulphurization of low-rank coals in Brazil. A reduction of sulphur content from 2.33 % in the feed coal to 1.08 % in the concentrate was obtained.

Table 3
Typical performance data for a DE-XRT.

Technique	Particle size (mm)	EP	Cut-point density (SG)	Ash (%)	Yield (%)	Reference
DE-XRT	+50	0.29	2.06	F [a]= 71.0 P[b] = 59.5 D[c] = NA	47.6	De Korte, 2013
Belt-type sorter (50 tph)	20–30	0.09	2.1	F = 28.3 P = 21.4 D = 66.0	84.5	Robben et al., 2014
		0.19	1.9	F = 29.5 P = 20.4 D = 61.6	77.9	
		0.14	1.9	F = 29.3 P = 20.9 D = 60.4	78.8	
Belt-type sorter (100 tph)	30–100	0.17	1.9	F = 43.8 P = 23.3 D = 73.5	59.1	Robben et al., 2014
		0.04	1.8	F = 43 P = 21.8 D = 68.4	54.4	
Chute-type sorter (100 tph)	30–100	0.11	1.7	F = 31.2 P = 19.5 D = NA	55	Robben et al., 2014
		0.13	1.6	F = 43.0 P = 25.7 D = NA	36.7	
		0.12	1.7	F = 33.8 P = 20.3 D = NA	51.6	
		0.11	1.6	F = 27.7 P = 21.1 D = NA	52.5	
DE-XRT	20–53	–	–	F = 24.12 P = 16.11 D = 48.09	75.2	von Ketelhodt and Bergmann, 2010
	53–75	–	–	F = 25.76 P = 16.82	82.5	

(continued on next page)

Table 3 (*continued*)

Technique	Particle size (mm)	EP	Cut-point density (SG)	Ash (%)	Yield (%)	Reference
	75–100	–	–	D = 67.88 F = 29.71 P = 16.67 D = 83.85	80.6	

[a] F is an abbreviation for Feed.
[b] P is an abbreviation for Product.
[c] D is an abbreviation for Discard.

4.2.2. Air table

The Standard Air Table discussed is mostly suitable for fine coal and offers EPM values in the range of 0.18–0.20 (Chavaldi et al., 2016). It is evident that for a wide range of ash contents (30–50 %) in the fine coal (+0.1–1.0 mm), the air table successfully reduced the ash value by 9–10 % points. Cicek (2008) established an improved air table to clean Turkish coal. The results indicated that the coal samples with three size fractions of 5–8, 3–5 and 1–3 mm can be efficiently beneficiated by this modified air table with EPM values of 0.21, 0.14 and 0.09, respectively, representing an acceptable separation performance.

Studies have been done using air tables in coarse coal fractions. Stotts et al. (1987) examined the dry separation of coal using an air table for 6.3 0–19.0 mm and observed EPM values in the range of 0.24–0.26. An air table was used for coarse coal separation with a top size of 50 mm by Killmeyer and Deurbrouck (1979) and with a top size of 19 mm in a plant with a capacity of 1200 t/h by Wright (1985). Zhou et al. (2021) claimed that coal of 6–38 mm is the best range size for an industrial separation scale air table separator, so that EPM values of about 0.13–0.23 can be achieved. Honaker (2005) revealed that 70–90 % of + 6.3–50 mm coal with a relative density higher than 2.0 kg/m^3 could be removed using an air table. A reduction of sulphur content from 2.33 % in the feed coal to 1.08 % in the concentrate was obtained.

4.2.3. KAT

The KAT is a modified air table mostly applicable to fine coal. This process can effectively remove produce clean coal with ash values ranging from 7–10 %. A stable separation efficiency is observed with EPM values varied from 0.08 to 0.12 and 84–90 % yield (Jambal et al., 2017). Two KAT air table separators were used for 1–5 mm (3.7–5 t/h) and 5–10 mm (5–31 t/h) raw coal cleaning of the Naryn Sukhait mine (Mongolia) by Jambal et al. (2016). In the results the ash content of 1–5 mm coal was reduced from 35.6 % to 12 %. Meanwhile, the ash value of 5–10 mm particles was reduced from 48.4 % to 9.4 %. Therefore, the KAT air table separator can effectively remove gangue from fine coal.

4.2.4. AKAFLOW

AKAFLOW is the result of a modification to a conventional air table for a coal size range of minus 3 mm (Akbari et al., 2020). EPM values are scarce in literature but yields of 73.5 % are possible with a reduction in ash value from 29.5 % in the feed to 18.3 % in the product (Wotruba et al., 2010). Another study shows an ash reduction to 25.8 % in the concentrate from 47.5 % in the feed with a 54.4 % yield (Wotruba et al., 2010).

4.2.5. FGX

The FGX, an enhanced air table developed in China, is proficient in beneficiating coarse coal, exhibiting separation with EPM values ranging from 0.2 to 0.3. Zhang et al. (2011) extensively evaluated the FGX separator's performance in handling Illinois Basin coal. Their findings highlighted the FGX's efficiency in beneficiating raw coal within the 6–75 mm size range, achieving a density cut of 1.98 and an EPM of 0.17. Subsequent research by Akbari et al. (2018) explored the development of a comprehensive dry processing plant flowsheet for raw coal beneficiation. This design incorporated a rotary breaker for reducing ROM coal size below 75 mm before its optimal use in the FGX separator. The FGX middling stream underwent re-crushing to enhance coal particle liberation (1.0–6.3 mm) for further cleaning in the second stage by the FGX. The resultant concentrate exhibited an ash content of 16 %, derived from a feed initially possessing 33.4 % ash content. De Korte (2013) investigated the FGX's applicability for South African coal types, yielding an EPM of 0.22 with a 70.8 % yield and an improvement in ash content from 40.4 % to 31.9 %.

4.2.6. ADMFB

The EPM value of the ADMFB is reported to be in the range of 0.04–0.12 which is the best when compared to the other dry methods available. It also provides the most flexible SG_{50} values. High magnetite losses and complicated dense medium recovery, cleaning, recycling (and drying) can lead to operational difficulties and larger capital and operation expenses (Yang et al., 2013). An example of an ADMFB is the Bohou unit, implemented in China, and has proven effective for beneficiating 13–200 mm coal (Zheng, 2016). Designed for 500 t/h, it can successfully separate coal at a cut point of 1.58 g/cm3 with feed coal containing less than 5 % moisture, producing clean coal of 9.85 % ash content; the separation has an EPM of 0.05–0.08.

ADMFB has been widely used for cleaning various kinds of coal with particle sizes of 1–100 mm. Luo *et al.* (2001) used the ADMFB process to separate 6–50 mm coal particles with an EPM value of 0.05. Duan et al. (2018) used ADMFB for pyrite recovery from 13–50 mm and 6–13 mm coal fractions and achieved recovery rates equal to 81.69 and 79.51, respectively. Sahu et al., (2011 studied the stability characteristics of different shapes of fluidized beds and established an ADMFB system to separate 6–25 mm coal particles. Luo et al. (2007) and Zhao et al. (2017) sorted coal of sizes 6–50 mm and 10–100 mm at a separating density of 1.5 g/cm^3.

Fu et al. (2019) performed experiments on a pilot scale ADMFB with four coal types in 25–50, 13–25, 6–13, and 2–6-mm size ranges. A close-to-perfect partition curve was observed for the 25–50 mm coal with an EPM value of 0.03, showing exceptional separation performance. For 13–25 mm and 6–13 mm coals, the EPM reported 0.07 and 0.10, respectively. The EPM for 2–6 mm coal was not calculated due to its 75 % partition coefficient being unavailable. From this, it is noted that EPM increased with decreasing particle size, independent of coal type. This can be attributed to rising gas bubbles, where fine coal particles fall into the bubbles. Moreover, the cut-point density also increases when particle size decreases. Separation densities of 1.85, 1.90, 1.95 and 2.05 were reported for the 25–50, 13–25, 6–13 and 2–6-mm PSD ranges, respectively. An increased cut-point density allows more impurities to remain in the concentrates and hence lowers the quality of the clean coal product. In conclusion, the separation efficiency of ADMFB reduces with reducing coal PSD, not only because of EPM and cut-point density increases but due to the variation of partition coefficients above 2.0 and 1.3. This may be attributed to bubbling behaviour and back mixing of the medium suspension preventing efficient separation of finer coal particles (Luo, *et al.*, 2001; Mohanta et al., 2011). Similar outcomes were reported by Azimi et al. (2017), that feeding finer coal particles (2.8–5.6 mm) deteriorates the separation efficiency and leads to higher product ash contents compared to larger particles (5.6–13.2 mm).

Chikerema and Moys (2012) affirmed the influence of particle size and shape on ADMFB separator efficiency when using a mix of magnetite and silica. They noted that larger particles (37–53 mm and 22–31.5 mm) exhibited faster and more efficient separation, averaging an EPM of 0.05, compared to smaller particles (16–22 mm and 9.5–16 mm). However, a reduction in particle size led to higher EPM values and a consistent shift in the cut density. The study emphasized that particle shape, though challenging to control, significantly impacted the

Table 4
Performance data for some commercially available dry coal gravity separation methods.

Technique	Particle size (mm)	EPM	Cut-point density (SG)	Ash (%)	Yield (%)	Reference
Air Jig	12.7–50.8	0.16	2	F[a] = 15 P[b] = 13 D[c] = 51	–	Weinstein and Snoby (2007)
Air Jig	−19	0.21	2.2	F = 21 P = 7 D = 60	–	Weinstein and Snoby (2007)
Air Jig	1–15	–	–	F = 38 P = 20 D = 69	59.8	Boylu et al. (2015)
Air Jig	−4	–	–	F = 32 P = 26 D = 55	60.5	Boylu et al. (2013)
Air table	−1	0.18–0.20	1.70–2.01	F = 31–50 P = 21–37	40–60	Chavaldi et al. (2016)
Air table	0.15–1	–	–	F = 34 P = 30	66	Kumar et al. (2010)
Air table	1.4–6.3	–	–	F = 23 D = 77–80	80	Patil and Parekh (2011)
FGX	0–80	0.13	–	F = 28 P = 18 D = 80	86.87	Zhao et al. (2014)
FGX	1–6.35	0.25–0.36	1.70–2.01	F = 31–36 P = 14–15 D = 53–60	–	Akbari et al. (2020)
FGX	0–80	0.145	1.66	F = 9 P = 1 D = 29	71.24	Yu et al. (2016)
FGX	4.75–63.5	0.17	1.98	F = 23 FS[d] = 4 P = 12 PS[e] = 3	–	Zhang et al. (2011)
FGX	+6.4	0.25	1.8–2.2	F = 18 FS = 2 P = 11 PS = 1	76.8	Honaker et al. (2008)
FGX	6–50	0.22	2	F = 40 P = 32 D = 60	70.08	De Korte, (2013)
KAT	5–10	0.08–0.1	1.8–2.0	F = 44 P = 8	–	Jambal, et al. (2017)
KAT	1–5	0.1–0.12	1.8–2.0	F = 34 P = 9	–	
AKA-FLOW	−3	–	–	F = 30 P = 18	73.5	Wotruba et al. (2010)
AKA-FLOW	0.05–3	–	–	F = 48 P = 26	54.4	Wotruba et al. (2010)
ADMFB	13–25	0.115	–	F = 39 P = 32	71–75	Mohanta et al. (2015)
ADMFB	10–100	0.055	1.49	F = 24 P = 4	67.88	Zhao et al. (2017)
ADMFB	3.35–5.6	0.03– 0.1	1.6	F = 14 P = 6	90	Choung et al. (2006)
ADMFB	3–6	–	–	F = 22 P = 10	77.45	Zhang et al. (2020)
	2–3	–	–	F = 21 P = 10	81.52	
	1–2	–	–	F = 19 P = 12	83.65	
ADMFB	3–6	0.13	1.87	F = 46 FS = 3 P = 31 PS = 2.6 D = 70 DS[f] = 3.4	89.26	Fu et al. (2016)
ADMFB	6–80	0.055	1.42	F = 16 P = 4	67	Zhang et al. (2014)
ADMFB	6–25	0.12	1.68	F = 40 P = 32–36	60–72	Sahu et al. (2011)
ADMFB	3–6	0.07	1.62	F = 36 P = 13 D = 67	50.79	He et al. (2015)

(continued on next page)

Table 4 (*continued*)

Technique	Particle size (mm)	EPM	Cut-point density (SG)	Ash (%)	Yield (%)	Reference
	6–10	0.055	1.71	F = 36 P = 12 D = 69	56.83	
	10–13	0.05	1.80	F = 36 P = 11 D = 71	61.24	
ADMFB	6–300	0.05–0.07	1.3–2.2	F = 39–46 P = 16–18 D = 64–68	41–56	Luo and Chen, (2001)
SEP-AIR	1–100	0.1–0.17	1.78–1.90	F = 13–19 P = 7–15 D = 51–70	85–93	De Korte (2018)

[a] F is an abbreviation for Feed;
[b] P is an abbreviation for Product;
[c] D is an abbreviation for Discard;
[d] FS is an abbreviation of Feed sulphur content;
[e] PS is an abbreviation of Product sulphur content;
[f] DS is an abbreviation of Discard sulphur content.

ADMFB's performance, particularly in the separation of 16–22 mm particles of various shapes. Three different particle shapes, including the flat, blockish, and sharp-pointed prism, were investigated by Chikerema and Moys (2012). A small surface area to volume ratio is observed for the blockish particles making them less subject to the effects of viscosity. Therefore, the blockish shapes separate more effectively than the other shapes considered.

Fu et al. (2016) examined the feasibility of using an ADMFB to separate 3–6 mm fine coal and expand its lower separation limit with the modified magnetite powders. In this study, four types of magnetite powders (0.3–0.4 mm, 0.225–0.3 mm, 0.15–0.225 mm, and 0.074–0.15 mm) were used. The results showed a significant reduction of the ash content from 45.92 % to 31.29 % and total sulfur from 3.02 % to 2.57 % with a clean coal yield of 27.33 % using the 0.074–0.15 mm magnetite particle-size fraction. Although the ADMFB with improved magnetite powders shows satisfactory performance for 3–6 mm, it is difficult to obtain a purified clean-coal product with a low-ash content. It becomes clear that a practical technique for purifying coal in smaller fractions must still be found, and further investigation is required to improve upon the performance obtained using these methods on an experimental scale.

Jiang et al. (2019) examined the movement and separation process of particles in different densities within the bed. The bed was divided into five layers according to its height. There are particles with a density lower than the separation density existing in the heavy product. There are also particles with a density higher than the separation density existing in the light product during the sorting process, resulting in pollution of concentrate and loss of coal. During the actual production process, the feeding position, media features, separation time and gas velocity have important effects on the fluidization characteristics and separation process of coal particles in ADMFB, thus, affecting the beneficiation of coal. The particle characteristics and composition of medium materials are significant factors that affect bed density. The pivotal standards for selecting a suitable medium include the composition, particle size, viscosity, cost, recoverability, and ease of cleaning. Previous studies on ADMFB have employed magnetite (45–500 μm) and fine coal (−1 mm) to create a suitable dense medium (Sahu et al., 2009). Magnetite is used to attain the required cut densities. Still, its recovery and recycling are problematic because it attaches to the surface of the coal and gangue particles, and their surfaces become contaminated. When using coal with a surface moisture content of more than 2 %, some challenges may emerge. Magnetite is hydrophilic and readily attaches to a wet coal surface, thus affecting the quality of fluidization due to an increased viscosity (Luo et al., 2010; Mohanta and Meikap, 2015). Agglomeration of the magnetite occurs because of its magnetic features (especially during recycling), reducing contact efficiency between the particles and the air and affecting particle dispersal and growing non-uniformity in the bed density. The polluted medium may also be difficult to recover or only be liberated with difficulty. Subsequently, the bed fluidization and sorting performance is inclined to decrease, and the operating cost is enhanced (Luo et al., 2010).

To achieve an optimized fluidized, different monodispersed mixtures of particles have been treated as the medium materials (Wei et al., 2003; Firdaus et al., 2012; Oshitani et al., 2013; Luo *et al.*, 2001; Zhao et al., 2012). It is certified that the separation density can be controlled by changing the composition of medium particles (Luo and Chen, 2001; Tang et al., 2009). Fu et al. (2019) mixed fine coal particles with magnetite in two mass fractions to generate two kinds of medium material with a fine coal content of 12.08 % (A) and 20.88 % (B). The results of this study revealed that the cut-point density could be reduced by 0.05 with the latter medium mixture (B), along with an increase in EPM (by 0.03).

The interest in the use of ilmenite (FeTiO3) as a dense medium in ADMFB lies in its high specific gravity (SG) of 4.5–5 g/cm3, along with its typically smooth pebble-like structure (Wills, 2016). Ilmenite is hydrophobic and paramagnetic; therefore, it does not readily attach to a hydrophilic mineral and can be recovered using magnetic separation (Drzymala et al., 2007; Wills and Finch, 2016). Kalenda et al. (2019) focused on using ilmenite as an alternative dense medium in the ADMFB. They found that ilmenite as a medium (63–355 μm) generated cleaner surfaces and higher recoveries at higher moisture contents than magnetite.

During the ADMFB process, a suitable size range of medium particles is needed in conjunction with the optimum gas flow rate to achieve the best performance. Mohanta and Meikap (2015) compared the different magnetite powder sizes with performance parameters for two coal-size fractions. The results showed that distinct size fractions of the same feed coal respond differently with the same size fraction of medium particles and vice versa. Misplacement of clean coal to the high-density discards increases as the medium particle size reduces, leading to separation performance reduction. Considering the EPM values and different performance criteria, the size magnetite powder of 106–150 μm is the most appropriate for coal cleaning in the size range of 13–50 mm.

Investigations into the applicability of the ADMFB for the South African small coal market yielded similar results. Hughes et al. (2017) studied the effects of magnetite-to-coal ratio and vibration on + 5.7–13.2 mm coal from the Witbank coalfield. These studies show that minimum fluidization is affected by changes in the amount of dense medium and vibration. However, the overall performance is not enhanced. Similar studies were conducted by Diedericks *et al.* (2022) but also included minus 6.7 mm particle size ranges from the Witbank coalfield, concluding that larger PSDs perform better, but adding vibration and amending the amount of magnetite yield minimal improved separation. Different dense medium types (magnetite, sand and fine coal) were investigated for minus 5.6 mm Witbank coal beneficiation in a study by Langner *et al.* (2018). An improvement in coal quality was observed, but differing media and adding vibration did not significantly increase separation efficiency.

4.2.7. SEP-AIR and NPPS

The SEP-AIR can produce a product at EPM values ranging from 0.10 to 0.17 and provides options for broad PSD applications (1–100 mm) and increased productivity. This method can obtain 85–93 % yields with an ash content reduction ranging from 13.1–19.0 % to 7.0–14.8 % and a cut-point density of 1.78–1.90 (De Korte, 2018).

The NPPS is a recently introduced technique. Therefore, a need emerges for further investigation into the optimization of its performance with the use of modelling techniques. Stanczyk (2020) suggested a numerical model to explain the operation of the NPPS to accurately predict the separation results. The model computes the trajectory of movement, velocity, and acceleration of individual particles, considering the feed material's properties and the device's operating variables. Stanzcyk et al. (2021) examined the effect of certain operating parameters on the performance of an NPPS coal separator. The results show the possibility of a 10–25 % reduction in ash content. The calorific value of the sorted particles was increased by 5–40 %, while a minimal output yield of products (60–70 %) was maintained.

4.2.8. Air-gravity separators in the experimental phase

Table 5 provides the performance data of dry density processes still in the experimental and developmental stages.

It is challenging to beneficiate the fine coal for a size smaller than 6 mm using the traditional ADMFB. A magnetically stabilized fluidized bed introduced by Fan et al. (2001) and a vibrated ADMFB investigated by Luo et al. (2008) presented to tackle this obstacle. However, these fine coal dry cleaning processes all meet limitations in industrial applications due to unmanageable external factors and low processing capacity. The vibrated fluidized bed (VFB) enhances gas–solid fluidization by applying external vibration, improving gas–solid contact compared to conventional fluidized beds (Dong and Beeckmans, 1990; Savage, 1989; Wank et al., 2001). Optimal operation of the DMVFB exhibits effective separation for fine coal below 6 mm, achieving an EPM value of 0.07, surpassing the efficiency of a wet jig at 0.11 (Luo et al., 2008). Consistent findings are reported in the research conducted by Hughes et al. (2017) and Diedericks et al. (2022).

Winnowing, however still in the experimental phase, has shown satisfactory results for beneficiating coal in both the coarse and fine coal fractions. With EPM values ranging from 0.065 to 0.25, cut-point densities of 1.76–1.97 and a product ash value ranging from 22–39 % from a feed of 28–46 % (Sahkre et al., 2018). Studies on the method of winnowing for the fine coal fraction are underway in South Africa at the NWU by Morgan and colleagues (from 2019, 2020, 2021).

Studies showed that DRC can clean 4–6.35 mm fine coal with an EPM value of 0.04 (Galvin, 2004; Macpherson 2011; Macpherson et al., 2010). Galvin et al. (2010) reported that the DRC is much less sensitive to size compared to other gravity methods. In the inclined settling zone, vibration aids in particle re-suspension in the DRC. It contributes to diminishing the bed voidage and the minimum fluidization velocity (Marring et al., 1994). Luo et al. (2008) and Macpherson et al. (2011) effectively separated dry coals sized between 0.5–6.0 mm and 1.0–6.35 mm, respectively, achieving an EPM of 0.07, utilizing a vibrated fluidized bed with fine magnetite and sand dense medium. The Reflux Classifier with an air-sand medium and vibration also has effective separation performance for 1–8 mm fine coal (Macpherson et al., 2010; 2011).

Density-based separation can be obtained by increasing the density of the fluidizing gas, and this is performed through the addition of a dense medium such as sand (2,600 kg/m^3 with a size range of 355–125 μm) and magnetite (5,100 kg/m^3 and a size range of 212–150 μm). Adjusting the ratio of air to the dense medium can be used to set the density of the fluidizing medium and, thus, the cut-point of the separation (Macpherson and Galvin, 2010). Macpherson and Galvin (2010) examined the efficiency of different dense media (magnetite and sand) and adding of vibration in a DRC. Using sand medium accompanied by vibration resulted in superior separations compared to the absence of vibration and the use of a magnetite medium. The amalgamation of a sand-dense medium and vibration demonstrated the most effective separation performance, achieving an EPM value of 0.07.

Many of the dry-cleaning techniques for fine coal show promise in separation results. However, some obstacles are encountered when considering industrial applications. These relate to dense medium recovery, product purification and capacity. In general, no effective method can beneficiate the minus 6 mm coal sizes.

4.3. Magnetic separation

In recent years, desulfurization and separation methods for fine coal

Table 5
The performance data for experimental dry coal gravity separation methods.

Technique	Particle Size (mm)	EPM	Cut-point density (SG_{d50})	Ash (%)	Yield (%)	Reference
Vibrated ADMFB	6–3	0.19–0.225	1.52–1.89	F[a] = 41 P[b] = 16 D[c] = 70	36.62–37.50	Yang et al. (2013)
	3–1	0.175–0.195	1.52–1.89	F = 40 P = 14 D = 71		
Vibrated ADMFB	0.5–6	0.07	1.81	F = 18 P = 9	82.76	Luo et al. (2008)
Magnetically stabilised ADMFB	0.5–6	0.065	1.516	F = 31 P = 13 D = 62	61.3	Luo et al. (2002)
Winnower	2–100	0.065–0.25	1.76–1.97	F = 28–46 P = 22–39 D = 38–60	30–80	Sahkre *et al.* (2018)
DRC	4–6.35	0.07	1.49	–	–	Macpherson et al., (2010
	2–4	0.13	1.530	–	–	
	1–2	0.23	1.650	–	–	

[a] F is an abbreviation for Feed;
[b] P is an abbreviation for Product;
[c] D is an abbreviation for Discard.

have become popular research topics in the dry coal preparation sector. Chemical and biological desulfurization technologies can remove inorganic and organic sulphur in coal. However, these technologies have issues, including high costs, long production cycles, and pollution. Physical desulfurization techniques can only remove inorganic sulphur and are considered more economical and practical (Çelik and Yildirim, 2000; Zhao et al., 2008). Numerous studies have been conducted regarding the application of magnetic concentration methods to remove gangue mineral and pyrite from coal (Fujita et al., 1981; Hucko and Maronde, 1982; Van Driel and de Kerk, 1983; Male, 1984; Zhang et al., 2015; 2017; 2020). For example, a study using lignite reduced ash content to 12.3 % from 35.6 % in an air-jig and magnetic separator combination (Order et al., 2003). Desulphurization efficiency depends on the magnetic susceptibility, density, particle size, magnetic field intensity and gradient. Jiao et al. (2009) investigated the relationship among these parameters in the desulphurization of fine coal. A direct relationship was observed between magnetic susceptibility and density. High-density coal exhibited opposite magnetic properties to low-density coal at the cut density of 1.6 kg/m^3. As fine coal decreased in size, the diamagnetic characteristic of low-density coal weakened while the paramagnetic attribute of high-density coal increased. Yildirim et al. (1996) demonstrated a decrease in sulphur content from 2.49 % to 0.39 % for low-rank and semi-coked lignite using RERMS. Saeid et al. (1993) reported an ash reduction of 40 % and a sulphur decrease of 10 percentage points in a 106–500 μm UK coal sample. Celik (2002) noted a decrease in ash from 39.49 % to 14.2 % and a product sulphur content of 0.41 % from a feed of 2.09 %.

While magnetic separation methods find some commercial application for shale and sulphur reduction in the + 0.5 mm particle size range (Zhang et al., 2017; 2020), obstacles include the need for fine comminution for optimal liberation, low feed moisture and strict feed preparation and presentation. As such, they may not be as efficient in separating clean coal from shale, more specifically pyrite (Zhu and Zhu, 2005; Wang and Li, 2004).

It has also been proven that coal pre-treatments like pyrolysis or microwave treatment can improve the efficiency of magnetic separation (Koca et al., 2000; Celik and Yildirim, 2000; Uslu et al., 2003; Uslu and Atalya, 2004; Zhang et al., 2015; Tripathy et al., 2017; Zhang et al., 2015; 2017; 2020;). Since pyrite is weakly paramagnetic and its separation from coal is difficult, it can be transformed into another form called pyrrhotite by heating. Pyrrhotite is strongly paramagnetic and can easily be separated from coal in only moderate magnetic intensities. Studies on pyrolysis prove that treating a lignite coal sample with pyrolysis enhances the magnetic properties of the mineral matter (Koca et al., 2000). After heat treatment and magnetic separation for a beneficiation process of Tavsanli-Omerler lignites, total sulfur, ash and volatile matter reduced from 3.98 %, 15.16 % and 39.37 % to 1.27 %, 8.5 % and 22.08 %, respectively, whereas the heating value increased from 5,877 to 6,727 kcal/kg (Celik, 2002).

As heating destroys the coal, it is impossible to transform the bulk of the pyrite into pyrrhotite. The use of microwave radiation to convert the pyrite in coal is an effective heat treatment approach and has the advantages of fast, selective heating and uniform heat distribution (Butcher and Rowson, 1994; Uslu *et al.*, 2002; Dwari and Rao, 2007; Waters et al., 2008; Ge *et al.*, 2013; Chen et al., 2019). The pyrite has a higher permittivity and heats up quicker than coal. Therefore, microwave pre-processing of pulverized coal can stimulate the quick pyrolysis of the pyrite in the coal and transform it into pyrrhotite (Uslu and Atalay, 2004; Waters et al., 2008; Zhang et al., 2015; Zhang et al., 2022). Zhang et al. (2017) showed that after a two-stage coal beneficiation process (0.5–0.25 mm), including microwave and magnetic separation, the pyrite removal was 20 % after 60 s and 60 % after 90 s of microwave treatment.

Zhang et al. (2020) explored the impact of feed size, microwave pre-treatment time, and background field intensity on the desulfurization of coal through high-gradient magnetic separation. Their findings indicated that extended microwave pre-treatment time facilitated the conversion of pyrite to pyrrhotite in pulverized coal, aiding the more efficient removal of sulphur components during the magnetic separation process. Extensive studies on microwave-enhanced magnetic separation for coal desulfurization suggest that microwave treatment can heighten the magnetism of pyrite, thereby enhancing the desulfurization effectiveness during magnetic separation (Ambedkar et al., 2011). Excessive pre-treatment (above 4 min) can cause further decomposition of the newly generated pyrrhotite into troilite (FeS) in the reaction system, resulting in a weakened magnetism of the pulverized coal. Zhang et al., (2018 found the same result. As the pulverized coal particle size decreases, there is a consistent increase in the desulfurization rate. This is due to finer particles allowing for the complete decomposition of sulfur groups within the coal, leading to a larger surface area for enhanced reaction completion. With increasing background field intensity, the magnetic force on the pyrrhotite becomes larger, and the sulphur components are more easily separated from pulverized coal. Uslu and Atalay (2004) observed that utilizing a 2-T magnetic field intensity in the magnetic separation of coal (−0.15 mm size) did not significantly decrease the sulfur content. Post-magnetic separation, the removal rates for ash and sulfur were 15.79 % and 22.29 %, respectively. Even with microwave heating at 850 W and 2.45 GHz, the increase in magnetic property was insufficient to enhance pyrite removal (37.46 %) via magnetic separation at 2 T. However, the inclusion of magnetite, known for its microwave absorption properties, notably amplified microwave heating and subsequently improved pyritic sulfur removal via magnetic separation. By incorporating 5 % magnetite, sulfur content was reduced by 55.11 %.

The high gradient magnetic separator and microwave desulfurization techniques for enhancing the magnetic properties of coal are still in the laboratory stage and have not yet reached commercial status. Therefore, developing an efficient and reliable method to desulfurize this type of coal is necessary. Table 5 provides a summary of the performance of magnetic separation discussed above.

4.4. Electrostatic separation

Much like the magnetic methods described above, most of the work on electro-static separation is developmental and only applies to fine particle sizes (Inculet et al., 1980; Masuda et al.,1984; Mukherjee et al.,1987; Finseth et al., 1993; Dwari and Rao, 2006; Trigwell et al., 2003). While particularly good ash reductions could be achieved, these investigations' main objective is removing sulphur rather than lowering the ash for a final product. Feed sulphur contents of between 1.5–2.5 % could be reduced to less than 1 %, albeit in a particle size range of below 45 μm.

Tao *et al.* (2010) reported the successful application of TBS in cleaning pulverized coal by reducing 13 per cent of the ash content of feed with 90 per cent combustible recovery. They also concluded that other impurities, such as sulphur and mercury, can be removed. Dwari and Rao (2008, 2009) revealed the results of coal cleaning (−300 μm) with a cylindrical fluidized bed tribo-charger with internal riffles. Coal was beneficiated from an ash value of 43 % to a product with 18 % and 33 % ash and 30 % and 67 % yield. Bada et al. (2010) reported the successful application of TBS for cleaning two types of pulverized coal samples (−177 μm) in South Africa.

Based on the available literature, surface pretreatment of coal emerges as an effective strategy to enhance the efficiency of triboelectric separation (Ma et al., 2020; Zhang et al., 2021; 2022; Xian *et al.*, 2021b). The principle behind the separation in triboelectric separation (TBS) relies on the variance in tribo-charges between different materials (He et al., 2020). According to Zhang et al. (2016), polymethyl methacrylate was identified as the optimal material for tribo-charging, augmenting the charge difference between coal and other minerals. He et al. (2020) highlighted that alterations in temperature and moisture can affect the tribo-charge difference of minerals. Xian et al. (2021) delved into the optimal temperature and humidity conditions for triboelectric separation of coal macerals. Surface modification using kerosene, diesel, acetic acid, and sodium stearate was also noted to impact the efficiency of coal triboelectric separation significantly (Ma et al., 2020). Wang et al. (2017) confirmed that the utilization of ethanol as a modified reagent notably amplifies the tribo-charge difference between clean coal and gangue minerals. Additionally, Li et al. (2016) observed a discernible enhancement in triboelectric separation results of coal fly ash following microwave heating, attributing it to alterations in the permittivity.

5. Conclusions

There are relevant economic, operability and environmental drives for the shift to processing coal on a waterless basis. Any advantages must, however, be weighed against any possible limitations, including densimetric properties and coal type, particle size and distribution, moisture content, feed presentation and certain operating parameters. Implementation should also consider the desired product specification, feed preparation, and separating efficiency and costs. Much investigation has been conducted into the various dry processing methods, and many processes are commercially available for specific applications and perform relatively well.

Dry coal processing methods are found to be useful in pre-concentration operations for destoning and production in small and remote or under-developed mining sites and areas with extremely dry or freezing conditions. These processes are most applicable to methods pertaining to the coarse coal (+6 mm) circuits with low moisture contents. Although the DE-XRT sorting method is promising for de-shaling and desulphurization, its application is still in the consolidation phase in the coal industry. These machines, however efficient, may need to be implemented in numbers to meet the throughput requirements, especially as PSD reduces. This significantly increases the capital and operating costs of the plant. The air jig is favourable due to its high capacity and ability to admit a large range in feed size. However, it only proves suitable for destoning applications and only when the fraction of near dense material is low. The FGX air table design is also applicable for coarse particles but usually demands the preparation of a closely sized feed with reduced moisture content. In parallel, the various air table designs (Standard, KAT and AKAFLOW) are more appropriate for processing the intermediate or fine particle sizes but require strict preparation. The efficiency of these air table variants is also significantly affected by the presence of near-dense materials and moisture, especially in the fine coal fractions.

ADMFBs exhibit notable separation efficiency and high capacity; however, their operation costs and sensitivity to moisture due to finely sized dense medium pose challenges. In contrast, air jigs, air tables, and SEP-AIR methods operate without requiring additional dense medium processing, offering larger capacities and lower processing costs. Nevertheless, their separation efficiency remains limited due to inherent constraints in the separation mechanism. Additionally, electrostatic and magnetic separation methods necessitate specific coal features and a certain level of dissociation, resulting in limited handling capacities. Consequently, they are primarily employed for specialized objectives, such as desulfurization, due to these constraints.

Given the above, the EPM values of dry processes do not compare well with the 0.020–0.025 achievable in a typical water-based beneficiation plant, and the comparatively high cut-points, dry processing still has a way to go when considering wide-scale industrial implementation.

The search for a suitable dry coal beneficiation technique for the arctic, arid, and remote regions is still underway. Many researchers worldwide are involved in this search, whether it be a new design or improvements to the methods discussed in this paper. Much investigation needs to be done regarding the feasible dry separation of fine coal particles and the large-scale separation of their coarser counterparts.

CRediT authorship contribution statement

Nikki Hughes: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Marco le Roux:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Quentin Peter Campbell:** Supervision, Resources, Funding acquisition, Conceptualization. **Fardis Nakhaei:** Writing – review & editing.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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