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Research Article

Evaluation of Wind Energy Recovery from an Underground Mine Exhaust Ventilation System

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Wind energy is a reliable renewable source of energy with significant technological advancements. However, recovering wind energy from waste and predictable sources remains untapped. Certain industrial activities emit pollutants while generating wind energy, presenting opportunities for cleaner energy utilization. This study investigates wind energy recovery from an underground mine's exhaust through experimental research and analysis. It revealed a drop in wind velocity at −2.5162 Hz frequency as distance increased. This frequency predicted a wind speed of 7.67 m/s at 1 m from the exhaust fan in a real mine. Theoretical calculations show significant wind energy potential of 1031.31 kWh over 13 hours, which is equivalent to 79.3 kW. Realistic estimates suggest 55.51 kW wind power can be recovered, yielding 721.63 kWh. Compared with previous studies in the mining industry, recovery potential varies based on site-specific factors. The study shows a recoverable power percentage of 28% theoretically and up to 19.8% realistically, highlighting wind energy's potential in underground mining. Moreover, the wind energy significantly contributes to the lighting system, enhancing energy efficiency. To optimize recovery, the ventilator fan system is upgraded, multiple fans are used, and optimizing the design is recommended. The study emphasizes continuous research and real-world implementations for energy savings. Utilizing wind energy effectively improves sustainability and reduces reliance on conventional sources, promoting a greener future for mining.

1. Introduction

The growing global energy demand has necessitated the development of new and efficient energy production technologies that can help harness the world's untapped energy resources with minimal environmental impacts [1]. Global energy demand is estimated to increase by 47% by 2050 as a result of population and economic growth [2]. Furthermore, according to Ritchie et al. [3], worldwide annual energy consumption in 2019 was 160 PWh, with renewable energy accounting for only a small portion of the total. Because industrialization is at the heart of developing economies, their energy requirements increase faster than those of developed economies [4]. Because industrialization is at the heart of developing economies, their energy requirements increase faster than those of developed economies [4]. In Africa, slow technological development has led power producers to fail to meet rising demand, resulting in fierce rivalry for energy produced between those using it for domestic and industrial purposes. As important as energy is to human survival, every country's socioeconomic development is inextricably linked to the quantity of energy available for use by its industries [4]. This highlights the importance of supplementing traditional energy production methods with modern renewable approaches in order to satisfy the world's ever-increasing energy demand [5]. Every other industrial sector has a direct or indirect connection with the mining sector, making it one of the most important sectors of the global economy. Because most materials mined are used in technological development and machine manufacturing [6], which are then deployed for secondary applications, the mining industry serves as the heart of the production and manufacturing sector. In 2017, satellite imagery was used to identify over 35,000 mining sites worldwide. Data validation studies conducted between 2000 and 2017 revealed that the satellite data gathered are 88.4% accurate [7]. During this time, 9,888 valid sites in 6021 regions of interest were visited, and future data collected showed that commodities or minerals were mined at different sites.

The mining industry, heavily reliant on fossil fuels for energy supply [6], presents a promising avenue for energy production and reduction of grid dependency. Globally, mining operations are estimated to consume 6.2% of total energy, with a substantial 40% utilized to overcome friction, amounting to 4.6 EJ annually [8]. Among the energy-intensive mining activities, grinding, haulage, ventilation, and digging stand out, with ventilation alone accounting for 1.035 EJ, are equivalent to 287.5 TWh of energy [8]. Given this significant energy consumption, exploring non-traditional applications for mining sites becomes imperative, seeking ways to continue benefiting communities even after mining operations cease. Repurposing mine infrastructure offers environmental advantages and instills confidence in the regions that previously relied on mining activities [8]. This exploration marks a crucial step toward fostering sustainable mining practices. Furthermore, mining companies often operate in remote regions with challenging climates, hindering the development of large towns and cities. The proximity of residences to mines is typically a direct result of the mining activities. However, the heavy reliance on constant mining operation for jobs and revenue, along with fossil fuel imports, can lead to decreased sustainability, particularly in developing nations [9]. Abandoned mining sites, in turn, are often seen as burdens, requiring costly cleanup once mining operations cease. Moreover, the high energy consumption in mining results in elevated production costs, impacting the profitability of underground mines [10]. Globally, electricity costs are a significant driver of mining expenses, and reducing energy usage can help mitigate commodity costs and improve profit margins. Large mining corporations have identified energy management as a crucial factor affecting both costs and operations, with energy accounting for over 20% of mining expenses [10]. In addition, underground ventilation systems consume a substantial amount of electricity, comprising 25% to 50% of a typical underground mining site's electricity consumption. The numerous appliances and fans used in these systems can easily exceed 10,000 kW of installed power [10, 11]. Given the high costs associated with ventilation and cooling, there is a pressing need for innovative energy recovery methods in mining operations.

Numerous studies have explored renewable energy technologies to offset fossil fuel usage in remote regions [12]. Even exploited underground mines hold potential for energy recovery despite weather and seismic challenges [13]. The Canadian Mining Innovation Council has successfully discussed using alternative fuels and renewable energy sources in mining [14]. Researchers have highlighted various energy sources available in mines, such as methane in ventilation air and geothermal energy from abandoned mines [13, 15]. Obracaj and Sas [13] have presented theoretical possibilities for energy recovery in mines. Also, Kalantari and Ghoreishi-Madiseh [16] have found that mine exhaust heat recovery (MEHR) can significantly save fuel costs in a case study. Other studies have evaluated water and ventilation system energy sources in mines [6, 17], contributing to mining safety and production enhancements. Clearly, these studies have shown the promising potential of renewable energy technologies in remote regions and fully exploited underground mines. The mining industry explores alternative fuels and renewables, identifying diverse energy sources such as methane and geothermal energy. Significant fuel cost savings can be achieved with advanced technologies. In addition, assessing water and ventilation system energy sources can enhance mining safety and productivity. This collective effort underscores the transformative potential of renewable energy adoption for a sustainable mining future.

Wind energy, a reliable renewable source, is projected to supply 20% of global energy needs by 2030 [18]. Wind turbines are vital components that convert wind's kinetic energy into electrical and mechanical power [19]. Despite slow initial progress, recent technological advancements have significantly improved turbine design, increasing power production and efficiency [20]. These innovations allow turbines to operate efficiently near buildings and utilize local wind flow [21]. Wind energy's flexibility offers an alternative to reduce fossil fuel dependency [22]. Researchers have explored innovative concepts, such as harnessing wind energy from unconventional sources, to generate sustainable electricity [23]. Studies have also demonstrated the feasibility of using horizontal-axis wind microturbines in transport systems, recovering energy while vehicles are in motion [23]. In addition, researchers have proposed an assessment method to determine wind energy potential based on wind speed, direction, and power data [24].

As stated previously, the ineffective distribution of air as a result of leakage in the ventilation systems during mining operation which until recently was wasted, and the high costs of ventilation, as well as cooling systems, show that mine operators have to make use of innovative wind energy recovery methods in the mines. Also, exhaust air is usually discarded into the atmosphere at a very extreme temperature than the ambient atmospheric air. A wind energy recovery system generates clean energy by converting waste wind energy from windy exhaust sources such as cooling towers and ventilation exhaust to generate useful electricity [25]. As long as the cooling tower (the wind source) is turned on, the exhausted air is always easily available, allowing wind energy recovery systems to produce energy that is predictable and continuous. In other words, exhaust air contains predictable and persistent wind characteristics [26]. As a result, a statistical examination of wind characteristics over time is not necessary. In addition, because it is anticipated that the turbine will spin at a constant speed, only a little amount of rotational speed fluctuation will occur negating the need for speed control [26]. Thus, it has higher turbine lifespan expectancy.

Previous studies have explored innovative approaches to harness wind energy from various exhaust systems, such as cooling towers and industrial fans [21]. For instance, Singh et al. [27] have examined a 3-bladed H-Darrieus wind turbine (HDWT) positioned at cooling tower outlets, emphasizing the potential of this alternative method for wind energy extraction. Ismail et al. [28] have reviewed the performance of exhaust air energy recovery wind turbines, converting wasted energy into electricity for rapid returns on investment, thereby reducing global CO_2 emissions. Similarly, Fazlizan et al. [21] have optimized the position and configurations of vertical-axis wind turbines (VAWTs) at cooling tower discharge outlets, achieving energy recovery and reducing fan motor power consumption. Hiremath et al. [25] have proposed utilizing wasted wind energy from industrial exhaust fans to meet energy demands. These innovative concepts address challenges related to irregular wind patterns and geographical limitations in wind energy utilization. In another work, Chong et al. [29] have introduced a microwind turbine system utilizing manmade wind resources without compromising cooling tower performance. Enclosure enhancements and laboratory tests confirmed its viability, with potential applications in existing cooling towers globally. These findings collectively offer promising solutions for energy recovery in various industries, including underground mines, where renewable energy technologies can play a significant role in reducing dependency on conventional fossil fuels and mitigating environmental impacts.

However, the application of wind energy recovery in underground mines poses unique challenges, including confined spaces, low wind speeds, and complex airflow patterns. As a result, some research studies have evaluated wind energy potential in mine ventilation systems using computational models and simulations. For instance, Wang et al. [30] have explored the optimal configuration of an air curtain device as an alternative refuge in underground mines, analyzing air flow and CO_2 diffusion through CFD modeling. Acuña and Lowndes [31] have also focused on developing algorithms to identify primary mine ventilation systems that minimize fan power costs while ensuring efficient performance. In the pursuit of optimal ventilation improvement measures, a ventilation improvement index (VII) was developed to integrate ventilation effectiveness and cost efficiency [32]. Zeqiri et al. [33] have compared ventilation systems in underground mines, emphasizing the importance of effective regulation for a safe microclimate during mining activities. Their research offers practical implications for calculating and regulating aeration in diagonal systems with main fan depression consideration. Other researchers such as Huaming et al. [34] have studied the impact of recirculation wind on underground mine ventilation systems. They used a depth-first search method to locate recirculation wind positions in the Dahongshan Copper Mine. The method aided in avoiding unidirectional wind effects on ventilation systems near mounted fans. Moreover, Cabana et al. [35] have explored effective energy generation in Ukrainian mining using wind-driven power plants. They demonstrate how technogenic airflows from industrial structures can meet 20 to 44% of a mining enterprise's power demand, offering sustainable energy solutions. Despite the challenges, wind energy recovery in underground mines offers opportunities to extend mining enterprises' lifespan by shifting focus towards energy generation. Incorporating innovative wind-driven power plants can transform mining enterprises from primarily coal mining to energy generation [30]. These advancements in renewable energy technologies hold promises for sustainable and efficient energy solutions in the mining industry.

In the quest to enhance ventilation systems and optimize energy efficiency in underground mines, valuable insights can be gained from studies conducted in subsurface mines. Adjiski et al. [36] have utilized "ANSYS" software to create a 3D CFD model, optimizing ventilation systems in subsurface mines. Their model considered factors such as face velocity, dead-zone areas, and air angle, leading to improved effectiveness, reduced energy consumption, and enhanced auxiliary forcing. Chen et al. [37] have proposed an innovative algorithm called the "improved differential evaluation (IDE) and critical path (CP) method based on the multivariable separate solution strategy (IDECP)" algorithm. It optimizes airflow divisions in subsurface mine ventilation networks, enhancing efficiency, interchanges, ruggedness, and flexibility. De Souza [38] has also demonstrated how to optimize ventilation networks in subsurface mines using the Hardy Cross and critical path methods. By considering various factors, his approach led to improved ventilation circuit planning and mining operations. These insights from subsurface mining studies offer valuable comparisons and recommendations that can be adapted to further advance our understanding and implementation of efficient ventilation systems in underground mines.

The reviewed studies have provided valuable insights into the technical feasibility and energy recovery potential of wind turbines for electricity generation, especially in industrial settings such as mines. However, it is evident that there is a need for more site-specific studies that analyze the wind energy recovery potential in underground mines. While existing literature offers theoretical and generalized models, there is a lack of practical implementation and performance analysis of wind energy recovery systems in specific underground mining environments. Therefore, there is a clear opportunity for conducting more case studies to document the practical implementation of wind energy recovery systems in underground mine ventilation systems. Such research endeavours would further advance our understanding and enhance the successful integration of wind energy recovery technologies in mining operations.

In light of the increasing energy demands in modern mining practices and the urgency to adopt sustainable solutions, this research aims to explore the feasibility and potential of recovering wind energy from the ventilation air expelled from underground mines. Taking the Chirano Mine in Ghana as a case study, this investigation seeks to establish innovative energy recovery methods that align with crucial sustainable development goals [8, 11]. While traditional wind energy generation technologies are well-established, the concept of wind energy recovery in mines remains relatively unexplored. Consequently, researchers have delved into designing both horizontal-axis wind turbines

(HAWTs) and vertical-axis wind turbines (VAWTs) to evaluate their potential for harnessing wind energy [29]. The primary objective is to assess whether wind energy recovery systems can effectively harness the kinetic energy of ventilation air and convert it into usable electricity [39]. This study undertakes a detailed assessment of the wind resource within the ventilation system, analyzing wind speed variations and patterns to determine wind energy availability and characteristics. Data on airflow rates, exhaust fan specifications, and relevant parameters are collected and analyzed to understand the potential energy available for wind energy recovery. Mathematical calculations are used to establish the energy recovery potential of the underground mine ventilation system, which are evaluated against the energy consumption values of the ventilation system. In addition, the research explores potential reutilization possibilities in the mining industry.

Undoubtedly, underground mining ventilation systems are vital for ensuring a safe working environment for pit workers, resulting in high energy demands [40]. Therefore, harnessing clean energy from this unnatural source through innovative applications of established technologies presents an exciting opportunity worth exploring [29]. The study on is of utmost importance due to its potential to harness renewable wind energy in underground mining operations. By harnessing wind energy from exhaust air, the research endeavours to improve energy efficiency, cost reduction, and environmental sustainability. Furthermore, it addresses critical knowledge gaps, making valuable contributions to renewable energy applications in industrial processes.

2. Methodology

2.1. Selection of Real-Life Underground Mine and Criteria Considered. The real-life underground mine used in this study was selected based on careful consideration of several key criteria. The following factors were taken into account during the selection process:

(i) Location and accessibility: The mine's location was an important factor in the selection process. We aimed to choose a mine that was easily accessible for conducting on-site measurements and experiments. Proximity to research facilities and logistical considerations were also taken into account.

(ii) Cooperation from mining authorities: Collaborating with the mining authorities was essential to gain access to relevant data and conduct experiments. We sought a mine whose management showed a cooperative and supportive approach to our research objectives.

(iii) Exhaust ventilation system design: The selected mine had a well-defined and properly documented exhaust ventilation system. The layout, fan capacity, and other relevant parameters of the ventilation system were assessed to ensure accurate data collection and analysis.

(iv) Wind energy recovery potential: We evaluated the wind energy recovery potential of the mine. Factors such as wind patterns, average wind speeds, and the feasibility of installing wind energy recovery systems were carefully considered.

(v) Representativeness: Regarding the mine's representativeness, we made efforts to ensure that the selected mine was comparable to other related mining and mineral sectors in terms of exhaust ventilation characteristics and wind energy recovery potential. This included analyzing available data on other mines with related energy recovery methods, ventilation systems, and climatic conditions. While the selected mine served as a case study for our research, we acknowledge that further studies in different mines would be necessary to establish broader generalizations about wind energy recovery potential in the underground mining industry. The representativeness of the selected mine was considered within the context of our study, and we aimed to provide relevant insights for the broader mining sector.

2.1.1. Selection of Representative Site: Chirano Gold Mine. For this study, the Chirano Gold Mine was chosen as the representative site. The decision to select the Chirano Gold Mine was based on several key factors. Firstly, the Chirano Gold Mine is situated in a region known for its significant wind resource potential. This makes it an ideal candidate for exploring the feasibility of harnessing wind energy from the mine's exhaust ventilation system. Secondly, the Chirano Gold Mine represents a typical underground mining operation in terms of size, layout, and ventilation requirements. It allows for a comprehensive assessment of wind energy recovery in a realistic mining environment, ensuring that the findings can be applied to similar operations worldwide. Moreover, the availability of data and cooperation from the mining company at the Chirano Gold Mine has played a crucial role in its selection. Access to detailed information on ventilation airflow rates, exhaust fan specifications, and other relevant parameters enables accurate and in-depth analysis of the wind energy recovery potential. By utilizing the Chirano Gold Mine as the case study, we aim to provide valuable insights into the practical implementation and performance of wind energy recovery systems in an underground mining context. The findings from this real-life application will contribute significantly to the understanding of wind energy's viability as a sustainable and efficient energy source for mining operations [31].

2.1.2. Chirano Gold Mine and Its Underground Ventilation System. Chirano Gold Mine is an open-pit and underground gold mine located in southwestern part of Ghana, 100 km southwest of Kumasi, which is Ghana's second largest city (see Figure 1) [41]. The town of Bibiani lies 15 km north-northeast of the mine area (37 km by road). Access to the mine from the capital Accra is via a sealed highway to

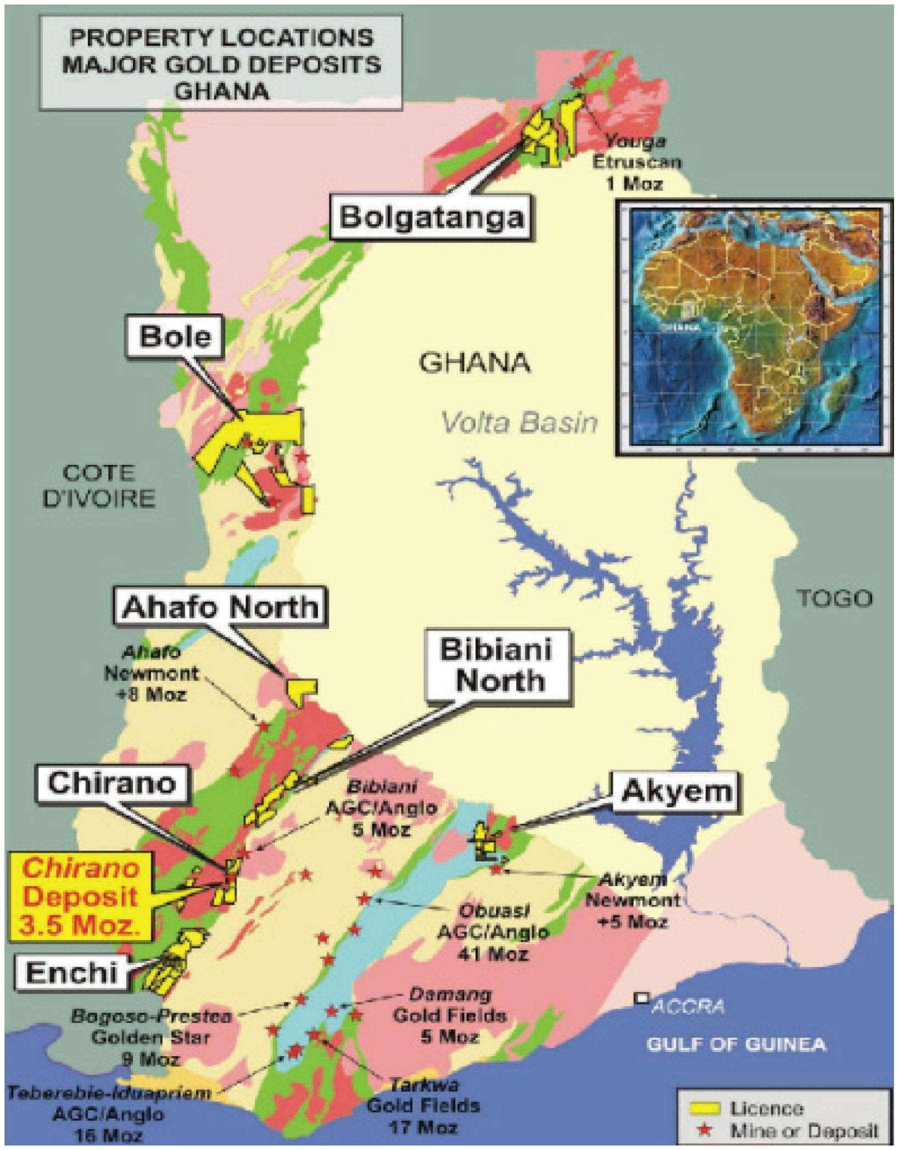


Figure 1: Mine location.

Kumasi and then sealed highway running southwest towards Bibiani and onwards to the town of Sefwi Bekwai. The final approach is through a 13 km gravel road whose junction is approximately 9 km beyond Sefwi Bekwai.

The Chirano Gold Mine, a significant gold producer in Ghana since 2005, employs open-pit and underground mining methods to extract gold ore. The mine development layout (Figure 2) includes a portal on the surface at approximately 2250 mRL for access to the underground mine. The main decline, ventilation intake, and ventilation exhaust shafts are situated on the footwall side of the orebody. The decline, measuring 6.0 m high × 5.5 m wide, serves as a major intake airway supplying half of the mine's required airflow. The remaining air inflow is provided by a ventilation intake shaft (FAW). The main underground infrastructure includes the decline, level development drives in ore and waste, and the fresh airway (FAW) and return (RAW) airway shafts. Fresh air enters the mine through the decline and FAW, while contaminated air is exhausted through the RAW.

(1) Mine Ventilation. Figures 3(a) and 3(b) illustrate the exhaust vent and primary ventilation distribution layout at the Chirano Underground Mine, respectively. The ventilation system intakes airflow from the surface through the main access decline and primary fresh airway (FAW) while exhausting air through the primary return airway (RAW). Both the FAW and RAW are situated on the east side of the orebody and extend from the surface to 2175 mRL. A drive at 2175 mRL connects the base of the primary FAW to the north and south extension raises below 2175 mRL, ensuring access on every level. The north and south RAW extension raises, developed at 4.5 m × 4.5 m, are designed to intersect the access drives on every level, each equipped with adjustable type regulators. The 2175 mRL RAW drive links the main RAW to the north and south extensions. Auxiliary fans

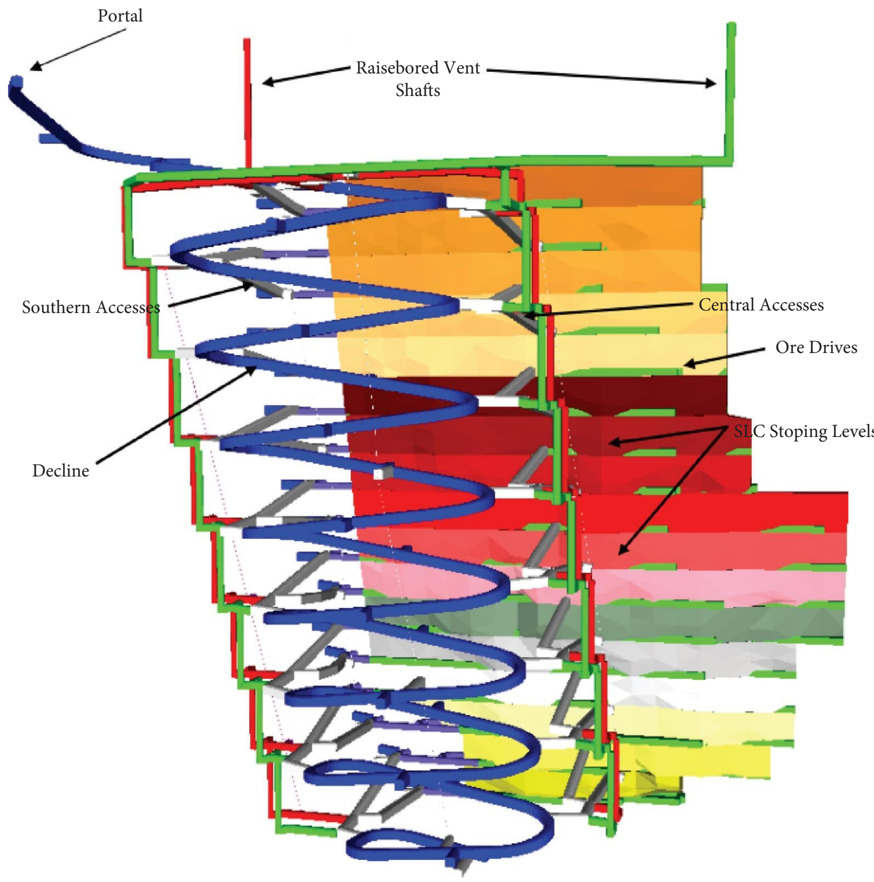


Figure 2: Mine development layout.

and ducts are installed adjacent to the FAW on each level's access x-cut, providing airflow to the working areas, while contaminated air is rejected to the RAW on the corresponding level.

2.2. Data Collection

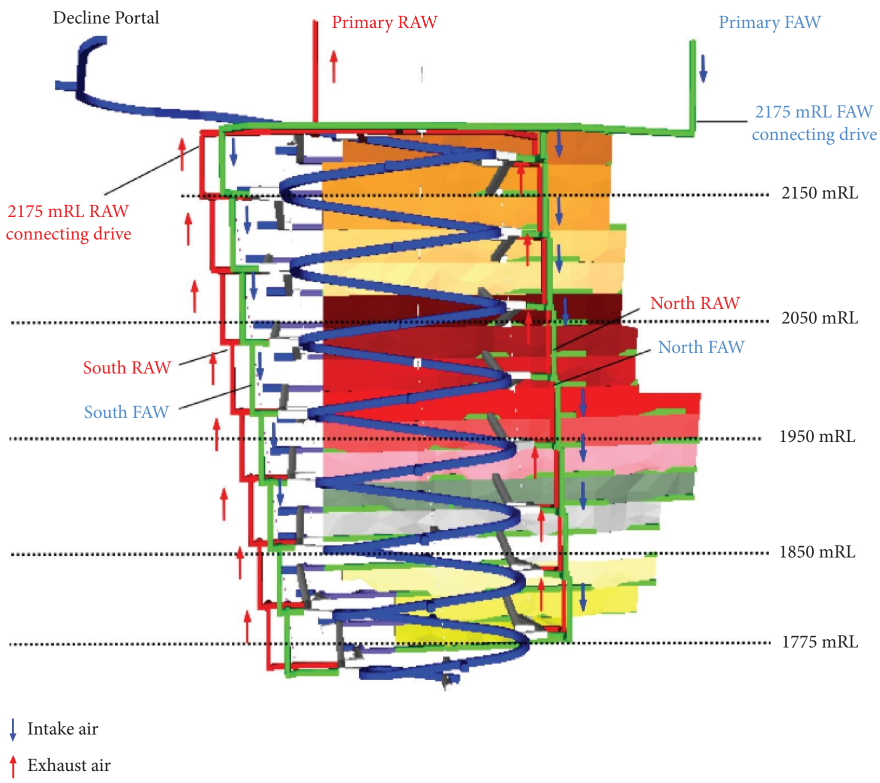
2.2.1. Wind Characteristics of Exhaust for Energy Capture from the Mine Site. Several underground mining sites install different ventilation capacities as well as ventilation system sizes based on several parameters [42, 43]. These parameters include the type of mineral mined, the equipment used in the underground facility, the fuel type that the equipment runs on, the type of machinery, the operations carried out underground, and the number of workers expected there [42, 43]. Ashanti Gold Corporation's Chirano Underground Mine's exhaust wind characteristics are measured and analyzed to establish a possible recovery. Data obtained from Ashanti Gold Corporation's Chirano Underground Mine are presented in Table 1.

2.2.2. Experimental Setup and Measurement Techniques for Wind Velocity Variation. The experimental setup and measurement techniques for studying the variation in wind velocity with distance from the exhaust fans in an underground mine ventilation system can be flexible depending on available resources and research objectives. In this study, the setup involved installing a Ventilator vom type fan as the exhaust fan at a fixed location within the ventilation system. A Technoline EA-3000 anemometer was placed at specific distances from the fan along a transect to measure wind speed variations. Wind velocity data were recorded using data logging equipment while measuring distances with a tape measure to understand the wind velocity variation. Multiple measurements were taken at various distances, and statistical analysis and graphical representations (regression analysis or scatter plots) were used to analyze the collected data and identify trends and patterns in the data. This approach provides valuable insights for potential wind energy recovery in the ventilation system.

(1) Experimental Observations of Wind Blown from a Fan. With an underground mine exhaust ventilation fan hugely dependent on the operation of a fan, studying the change in wind speed with respect to displacement is useful in predicting the variation in wind speed of an underground mine ventilation exhaust. An experimental model was used by Wang et al. [44] to predict the change in wind induced by the fan of a drone at a given distance away from the fan. The experimental setup made use of a fan and an anemometer.

Wang et al.'s [44] experiment is hereby adopted in this study but with a slight adjustment to predict the variation of

(a)



(b)

Figure 3: (a) Chirano Underground Mine's exhaust vent and (b) primary ventilation distribution layout.

Table 1: Underground ventilation exhaust information for Ashanti Gold Chirano Underground Mine.

Parameters	Values
Exhaust air velocity (volumetric flow rate)	200 m^3/s exhaust air
The cross-sectional diameter of the ventilation exhaust outlet	5 m
Exhaust air temperature records (min-max temperature value recorded)	Min 25/25 (wet bulb, dry bulb) max 27/27°C
Exhaust air pressure	2500 kPa
Ventilation exhaust orientation	Horizontal orientation
Exhaust air characteristics (in terms of air quality and composition)	CO, CO_2, CH_4, SO_2, N_2, NO_x, NH_4, and H_2S
Exhaust ventilation fans capacity (P_{vt})	1×280 kW fan (2 quantities)
Time duration for opening the ventilation system	7:00 am to 8:00 pm

Figure 4: Views of the experimental setup.

the underground mine exhaust wind with distance. As such, this study's experimental apparatus is similar to that of Wang et al.'s [44], consisting of a Ventilator vom type fan, a Technoline EA-3000 anemometer, and a tape measure. Figure 4 depicts an experimental setup in which a rope with metering calibrations was placed between two points from the location of the fan to a location where the wind induced by the fan is no longer experienced.

For measurements to be taken, it was ensured that the calibration commenced from exactly the casing frame of the fan. The Ventilator vom Type fan shown in Figure 5(a) is used to blow the air as the Technoline EA-3000 anemometer shown in Figure 5(b) drifted along the rope to measure the velocity of the wind in a horizontal orientation.

2.3. Wind Energy Resource Assessment. The lack of accurate and comprehensive data on wind resources is a significant obstacle to the use of wind energy in many parts of the world [45, 46]. Due to the varying nature of wind energy, the evaluation of wind resources for their potential use in energy production using wind turbines (WTs) is crucial for effective and practical energy production [47]. Wind resource assessment aids the calculation and estimations that help in establishing the feasibility of deploying a wind turbine for energy capture [48]. The assessment of wind resources is done based on location, wind speed, and wind characteristics. The main goal of a wind resource assessment is to determine the long-term wind characteristic at a given location to optimize energy harnessing [48]. Some crucial parameters considered during this study include the following:

(i) Global wind systems and ground roughness

(ii) Topography and roughness length

(iii) Contour lines and obstacles

(iv) Wind frequency distribution

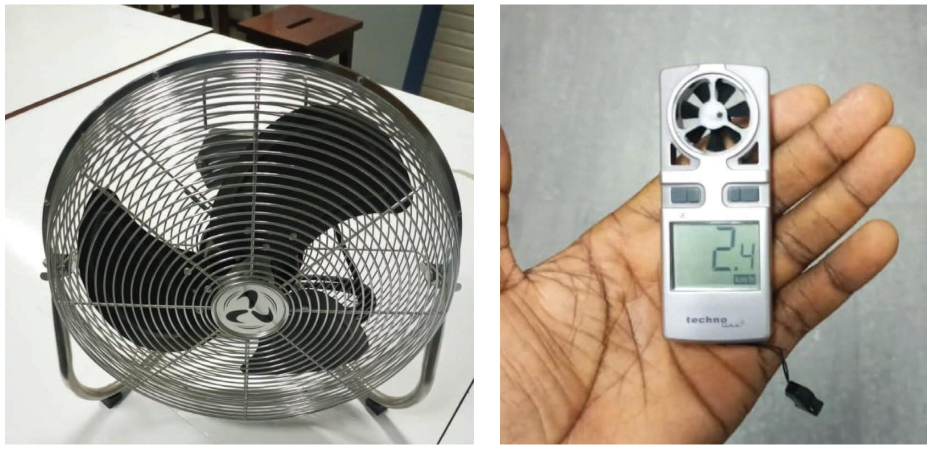
(v) Site classification and annual energy production

Most of these parameters result from natural interactions which are highly uncontrollable and unpredictable though heavily related to human activities especially those that influence global warming [49]. Ocean current and temperature variation in the atmosphere characterize the global wind system, whereas topography and roughness with contour lines and obstacles are associated with the interaction of wind with natural and artificial obstacles ranging from landscape nature and altitudes as well as habitats. Wind frequency distribution with site classification and annual energy production relate to the measured wind-related parameters which are analyzed to project possible energy production values [30, 50].

As much as artificial wind energy sources are unlikely to be affected by the aforementioned wind characteristics, there is a strong relationship between the characteristics of the artificial wind source and the natural wind source which is currently highly harvested [30, 45]. For instance, it is critical to know some vital characteristics of the wind energy produced such as the frequency of the wind, wind speed characteristics, air density, the area covered, and external or environmental factors that influence the energy production process.

2.4. Underground Mine Ventilation Exhaust Characteristics for Wind Energy Potential Estimation. Just like the natural wind, artificially induced wind sources also come with their own characteristics based on which their harnessing potential can be established. These wind characteristics are such that when not well considered may reduce the current established efficiency levels of wind energy systems and therefore need all the necessary attention. Moreover, estimating wind energy recovery from an underground mine ventilation system involves analyzing wind speed data, calculating wind power, and assessing energy demands. Factors such as wind speed and ventilation system energy consumption are taken into account to estimate the potential for wind energy recovery.

2.4.1. Airflow Velocity. According to Aminossadati, airflow in the underground mine ventilation system describes the circulation of air through the underground working environment to ensure a cool and fresh working environment in



(a) (b)

Figure 5: Major experimental setup components: (a) Ventilator vom Type fan and (b) Technoline EA-3000 anemometer.

working areas underground [51]. Air movement is monitored with an extremely high priority for air quality control purposes, and as a result, the airflow rate is often been measured in cubic meters per second (m^3/s) [52]. Equation (1) is then used for determining the underground air quality based on contaminant concentration [46]. This enables facility managers to manage and control air quality.

$$C = \frac{G_f}{Q_f}, \tag{1}$$

where C is the contaminate concentration in percentage, G_f is the contaminate flow rate, and Q_f is the ventilation flow rate.

Depending on the country of origin, there is always legislation on the threshold for contamination concentration in underground mining companies [53]. Prosser and Redden [54] investigated long-term ventilation planning and expectations as Wassa Underground Mine achieves production of 4000 pounds per day with trucks to haulage surface. In a study by Prosser and Redden [54], it was realized that in order to make the working environment conducive in the midst of increased underground activities in terms of haulage as personnel at Wassa underground mines, it was critical to increase the ventilation capacity also from the already existing 235.1 m^3/s capacity to 480 m^3/s. The quantity of air exiting the exhaust vent is crucial as it will determine the energy production potential from the recovery system. However, these measure parameters will remain unusable if not in terms of the velocity of the air. Therefore, it is necessary to use possible conversion methods to convert the volumetric flow values to velocity values, and the mathematical expression labelled equation (2) will aid in doing so [55].

$$Q = Av, \tag{2}$$

$$v = \frac{Q}{A}, \tag{3}$$

where v is the flow velocity, Q is the volumetric flow rate, and A is the the cross-sectional area of the flow channel (area of exhaust).

2.4.2. Ventilation Exhaust Area. The most important factors in the design of a new underground mine are the precise distribution of airflows, the positions and capacities of fans, and other ventilation controls that produce the right conditions throughout the system [51]. The ventilation system must be suitable to provide working extensions with enough ventilation as shafts and airways are built [56]. This results in a direct impact and relationship between the underground air quality and the size of the pipes used in air circulation (cross-sectional area of pipes) though high pressure with a small pipe is sometimes used. Most underground ventilation pipes as well as exhausts are often identified to have circular cross-sectional area [55], which is given as follows:

$$A = \pi r^2 \text{ or } \frac{\pi d^2}{4}, \tag{4}$$

where $d\,(r)$ is the diameter (radius) of the ventilation exhaust.

Using equations (3) and (4), the velocity of the exhaust air can be obtained.

$$v = \frac{Q}{\pi d^2/4}, \qquad v = \left(\frac{4Q}{\pi d^2}\right). \tag{5}$$

2.4.3. Airflow Density. Density is very important to consider in estimating the recovery potential as it is a vital parameter in calculating wind power. When air moves through the underground mine, it experiences significant changes in pressure, temperature, heat content, and density [57]. This makes the thermodynamic analysis of the mine ventilation system possible because the airflow processes in these scenarios are the same as the processes in a heat engine. With wind power being a function of air density, the density of air at a given sitting location is being determined for the feasibility analysis. Equation (6) indicates that density is highly dependent on pressure in fluids [55].

$$\rho = \frac{P_A}{RT}, \quad (6)$$

where P_A is the site air pressure, R is the specific gas constant for dry air (278 J/kgK), and T is the air temperature.

Therefore, at a location where the atmospheric pressure is different from normal, there is the need to calculate the density of the air too.

2.4.4. Temperature. Temperature is also an important parameter to look at. This analysis is not only because it affects the density of the air but also because it will be even more important in determining the material that will be used in the design of the wind recovery turbine fan. Temperature measurement from an underground mine exhaust is the primary determinant for assessing the quality of the air underground [58].

2.4.5. Period of Ventilation. Generally, the air supply to the underground mining site keeps happening as long as there are workers available in the working environment. Though some mines operate 24 hours a day for seven days a week, underground mines barely use such a schedule [59]. Underground mines are rather commonly found to operate for 12 to 16 h per day.

2.4.6. External or Environmental Factors. A well-planned and installed ventilation system has positive physiological and psychological impacts that improve worker security, comfort, health, and morale. The amount of air that will need to circulate in order to meet all health and safety requirements must be decided upon when constructing a ventilation system. The appropriate size of shafts, the number of airways, and the number of fans may be established once the quantity needed has been fixed. Fresh air flows down intake airways to the working areas where the majority of the contaminants are introduced to the air when it enters the system through the intake airshaft(s) or other connections to the surface [60]. As the exhaust containing numerous greenhouse gases exit, there is a high possibility of the wind speed being impacted by the wind in the external environment. This is highly dependent on the wind's speed as well as the direction of the outside wind, and this more probably is going to increase the inefficiencies in the energy recovery process than aiding the production of more energy.

2.4.7. Wind Power Availability for Extraction. The established wind energy formula shown in equation (7) will be applied in solving for the recoverable wind [61].

$$P_w = C_p \frac{1}{2} \rho A v^3, \quad (7)$$

where P_w is the theoretical wind power (kW), C_p is the Betz limit: the maximum theoretical efficiency for a wind turbine (59.3%), ρ is the density of the exhaust air (kg/m^3), A is the swept area of the potential turbine (m^2), and v is the velocity of the exhaust air (m/s).

2.4.8. Estimated Wind Energy Potential. To estimate the wind energy that can be recovered from the ventilation system, the wind power in equation (7) is multiplied by the duration of wind flow (t) as given in the following equation [61]:

$$\text{theoretical wind energy} = P_w \times t. \quad (8)$$

2.4.9. Turbine Efficiency. In this study, since a Ventilator vom type fan system is used for wind energy recovery, it does not involve a traditional wind turbine for electricity generation. Instead, the fan system itself harnesses the wind energy to aid in the ventilation process, increasing the efficiency of the ventilation system by utilizing the available wind power. Herein, the energy savings are evaluated by comparing the energy savings achieved with the wind-assisted ventilation system (P_w) compared to a conventional ventilation system (P_{vf}) powered solely by exhaust fans (see Table 1). The energy savings are given as follows:

$$\text{energy savings} = P_{vf} - P_w. \quad (9)$$

2.5. Evaluation of Recoverable Wind Energy from Underground Mine Exhaust Ventilation. Underground mine ventilation exhaust is described to come with complex characteristics which include pressure characteristics, temperature characteristics, velocity, and density, as well as chemical composition. Diesel-powered vehicles, the majority of which are used in underground mines, emit hazardous chemicals such as carbon monoxide (CO) and nitrogen oxides (NOx), as well as cancer-causing diesel particulate matter (DPM). The amount of airflow for an underground mine is typically determined by multiplying the engine power of the diesel vehicles used in the mine by the unit airflow requirement [62]. For example, Australia uses 0.05 to 0.06 m^3/s per kW of engine power while Canada uses 0.047 to 0.092 m^3/s per kW. The local mining Occupational Health and Safety (OHS) rules usually include these unit airflow requirements [62]. With all the aforementioned characteristics of the exhaust ventilation, the wind characteristics are comparable to the air blown from a fan.

2.6. Wind Speed from the Fan Exhaust. The variation in wind velocity with distance from the underground mine exhaust fans was investigated using an experimental setup, as shown in Figures 5(a) and 5(b). The purpose was to simulate the change in wind velocity (induced wind frequency) at the underground mining site. The experiment was conducted at different fan speed levels, specifically Level-1 and Level-3, to test the model's ability to predict wind frequencies accurately.

The Level-1 and Level-3 datasets obtained from the experiment are presented in Table 2. Initially, measurements were taken at 0 m from the fan frame, which recorded wind velocities of 6.31 m/s and 6.88 m/s for Level-1 and Level-3, respectively. Subsequent wind velocities were recorded at intervals of 10 cm (0.1 m) away from the fan's frame. It was observed that the peak wind speed value of the induced wind frequency was recorded at a distance of 0.1 m from the fan's frame; the regions with higher wind velocities are typically found closer to the exhaust fan's frame. These regions can be considered as potential locations for optimizing the placement of wind energy recovery systems.

This variation in wind velocity with distance from the exhaust fans is crucial for understanding the potential for wind energy recovery. It indicates the areas near the fans where the wind velocities are higher and where the potential for harnessing wind energy is more significant. Identifying such regions can help optimize the placement of wind energy recovery systems to capture and utilize the available wind energy efficiently. Identifying regions with higher wind velocities increases the potential for wind energy recovery, leading to higher energy generation and greater sustainability in the underground mining industry. Identifying regions with higher wind velocities near underground mine exhaust fans enhances wind energy recovery potential. Higher wind velocities signify greater kinetic energy, which can be efficiently harnessed by wind turbines for electricity generation. Strategically, placing wind energy recovery systems in these areas boosts electricity production and optimizes energy recovery from the ventilation system. This approach reduces reliance on fossil fuels, promoting a sustainable and ecofriendly mining operation. Overall, harnessing wind energy from these regions improves energy generation and sustainability while minimizing environmental impacts.

3. Results and Discussion

3.1. Analysis of Experimental Results. The result obtained from the experiment is crucial in predicting the energy recovery potential of the underground mine vent, but because the experiment was not conducted in a very well-controlled environment, it was subjected to errors. In the analysis of the data obtained, several data analysis approaches were deployed in the evaluation process. Also, in the experimental data analysis, trendlines and R-squared values, which are data analysis tools, were put into play.

Trendlines are lines that depict the pattern of data on a scatter graph or scattering dataset and show the direction and pace of the data being analyzed [63]. Trendlines basically show which single line or curve fits some data the best. On the other hand, an R-squared (coefficient of determination) value measure of goodness of fit is available for the class of exponential family regression models, which includes logit, probity, Poisson, geometric, gamma, and exponential [64].

Table 2: Wind speed from fan exhaust.

Distance (m)	Velocity (m/s)			
	Speed Level-3		Speed Level-1	
0	24.5	6.806	22.7	6.306
0.1	25.7	7.139	23.4	6.500
0.2	24.2	6.722	21.1	5.861
0.3	23.5	6.528	17.9	4.972
0.4	20.5	5.694	17	4.722
0.5	18.5	5.139	16.1	4.472
0.6	17.6	4.889	14.4	4.000
0.7	15	4.167	12.9	3.583
0.8	14	3.889	12.1	3.361
0.9	13.3	3.694	11	3.056
1	12.9	3.583	10.1	2.806
1.1	11.5	3.194	9.3	2.583
1.2	10.6	2.944	8.4	2.333
1.3	10.9	3.028	6.3	1.750
1.4	10.2	2.833	5.7	1.583
1.5	8.9	2.472	4.1	1.139
1.6	8.7	2.417	3.9	1.083
1.7	7.7	2.139	3.7	1.028
1.8	7.5	2.083	3.1	0.861
1.9	7	1.944	3	0.833
2	6.7	1.861	1.4	0.389
2.1	5.1	1.417	1.5	0.417
2.2	5.3	1.472	1	0.278
2.3	4.4	1.222	0.7	0.194
2.4	3.4	0.944	0.3	0.083
2.5	—	—	0	0.000

The R-squared reveals how much the variance of one variable relates to the variance of the other [65]. Therefore, it is used here to interpret the relationship between data points obtained and a trendline or line of best fit.

3.1.1. Experimental Data Representation. The data obtained from the experiment are plotted in Figures 6 and 7 for the fan speed levels 1 and 3, respectively.

The trendlines used in the two datasets for analysis were proved to have the linear expressions $y = -2.5613x + 5.6453$ and $y = -2.4711x + 6.4813$ for speed levels 1 and 3, respectively, as shown in Figures 6 and 7. Here, the negative slopes (−2.5613 and −2.4711) indicate that as the distance from the exhaust fans increases (x increases), the wind speed decreases (y decreases). The y-intercepts (5.6453 and 6.4813) represent the wind speed at the starting point (distance = 0), and they show the wind speed when the distance is minimal. The frequency of −2.5613 Hz was determined through frequency analysis of the wind speed profile data. Linear regression was then used to predict wind speed changes with distance from the exhaust fan, assuming a linear relationship between wind speed and distance. The values of −2.5613 Hz and −2.4711 Hz representing the dominant frequencies were then identified from the wind speed profile data. With the determined dominant frequencies, the linear regression analysis was conducted on the wind speed data at different distances from the exhaust fan [64]. The gradient of the linear trendline was then calculated using equation (10). For speed Level-1, the gradient of −2.5613 Hz was used, and for

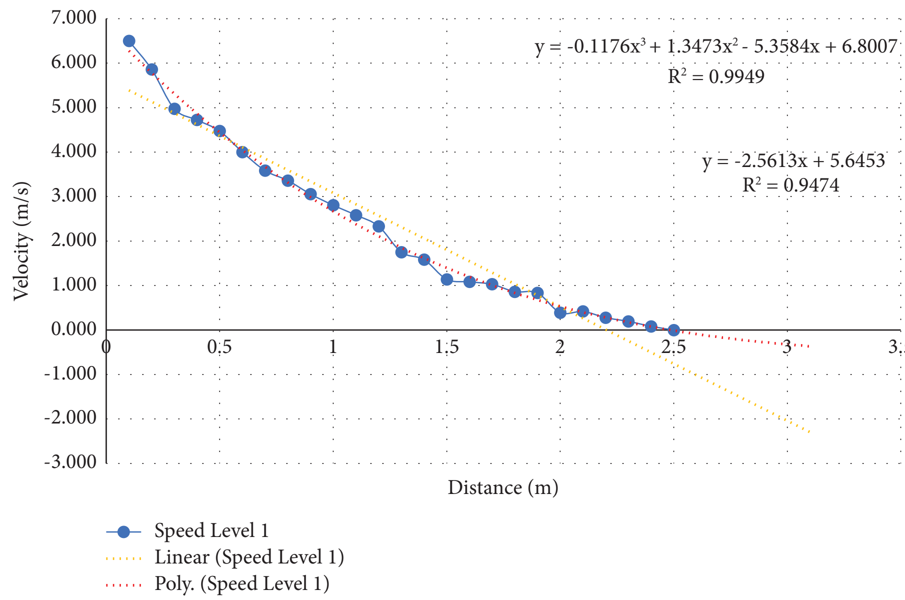


Figure 6: Speed level one of Ventilator vom Type fan frequency.

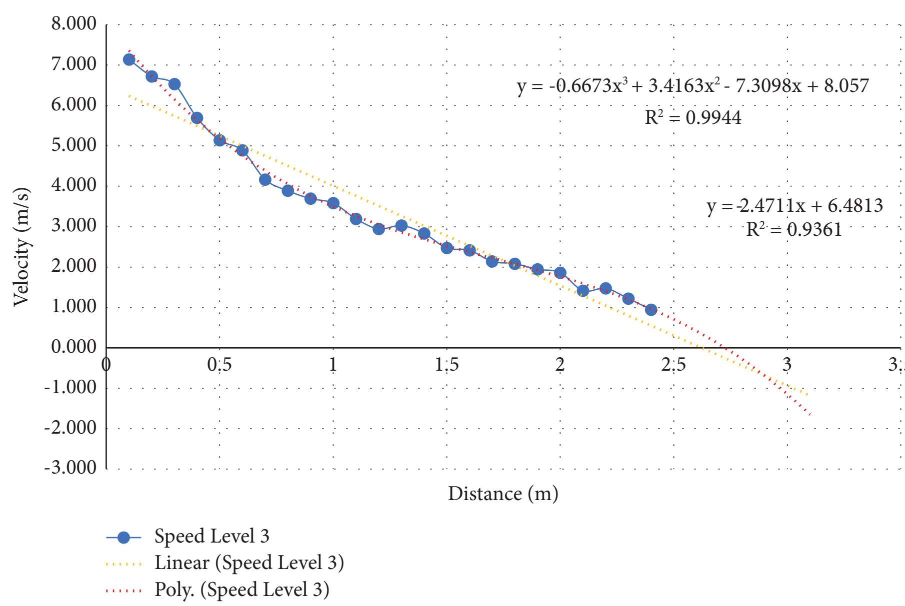


Figure 7: Speed level three of Ventilator vom Type fan frequency.

speed Level-3, the gradient of −2.4711 Hz was used. These gradients represent the rate of change in wind speed per unit distance from the exhaust fan for the respective speed levels.

$$\text{Gradient} = \frac{\text{velocity m/s}}{\text{distance (m)}}. \quad (10)$$

By utilizing the gradients (−2.5613 Hz and −2.4711 Hz), the change in wind speed with distance for each speed level is estimated. The wind speeds at different distances from the exhaust fan are estimated to gain insights into how wind speed changes as the distance increases.

According to Figure 7, the wind frequencies were, therefore, found to deviate slightly from each other, thus having a difference of 0.0902. The average of the two frequencies was also found to be 2.5162 Hz. Also, the *R*-squared values for the linear trendline were found to be close to perfection, that is, 0.9474 and 0.9361 for speed Level-1 and speed Level-3, respectively. This implies trendlines drawn were very close to representing the data accurately, therefore, based on the trendlines for further calculation and estimations will yield a near-accurate result. Figure 8 compares the trendline between the two speed levels studied, and it shows that the gradient of the lines is very close, which can be useful in predicting the outcome frequencies of other fans undergoing the same process.

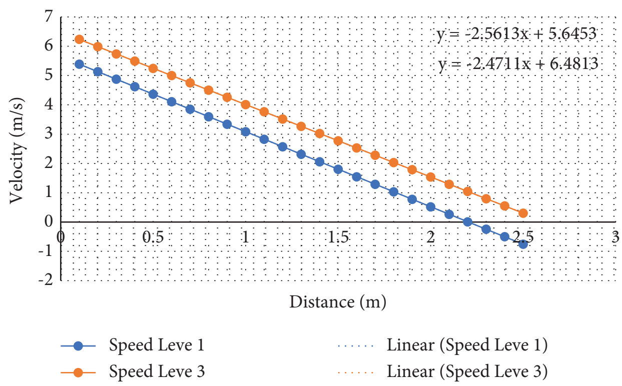


Figure 8: Comparison between the first level speed and the third level speed trendlines.

3.2. Estimated Wind Power and Energy Potential. Energy recovery systems are defined as the techniques used to recover energy that otherwise would have been wasted. The recovered energy can be stored and used as needed, reducing the need for additional fuel or energy sources and increasing the overall effectiveness of the system to which the technology is applied [66]. In order to lessen this load, it is crucial to use energy recovery systems [67]. Since wind energy is to be determined in this analysis, it is crucial to know the wind speed of the exhausted wind at the Chirano Mine. Using the volumetric flow rate $Q = 200\,\mathrm{m^3/s}$ and a cross-sectional diameter of ventilation exhaust outlet $d = 5\,\mathrm{m}$ in Table 1, the wind speed of the exhausted wind is calculated using equation (5):

$$v = \frac{4(200)}{\pi(5^2)}, \qquad v = 10.19\,\frac{\mathrm{m}}{\mathrm{s}}. \tag{11}$$

At a wind velocity of 10.19 m/s at a distance of 0 m from the exhaust fans with a frequency of −2.5162 Hz, the trendline for the wind speed with distance can be described using equations (12) and (13) as follows:

$$y = mx + c, \qquad 10.19\,\frac{\mathrm{m}}{\mathrm{s}} = -2.5162(0) + c, \qquad c = 10.19\,\frac{m}{s}, \tag{12}$$

$$\Rightarrow y = -2.5162x + 10.19, \tag{13}$$

where y is the wind velocity (dependent variable) and x is the distance from the underground mine exhaust fans (independent variable); equation (13) is thereby used to predict the drop in wind speed with distance from the turbine, and the results are presented in Table 3.

To avoid obstructing the free airflow from the exhaust ventilation duct or prevent compromising the efficient operations of the ventilation system, the wind energy recovery turbine must be sited at an appreciable distance from the exhaust fans so as to prevent any effect of turbulence on the ventilation fans. Therefore, with little observation from the experiment conducted, the wind recovery turbine can be sited between 1 and 2 m from the exhaust ventilation fans so as to capture a reasonable amount of the wind energy as compromising the ventilation efficiency is prevented. As a result, the wind speed at 1 m, which is 7.67 m/s, is selected for further energy calculation and estimations; this is shown in Figure 9.

Table 3: Wind velocity trend with distance from the exhaust fan.

Distance, x (m)	Wind velocity, y (m/s)
0.2	9.69
0.4	9.18
0.6	8.68
0.8	8.18
1	7.67
1.2	7.17
1.4	6.67
1.6	6.16
1.8	5.66
2	5.16
2.2	4.65
2.4	4.15
2.6	3.65
2.8	3.14
3	2.64
3.2	2.14
3.4	1.63
3.6	1.13
3.8	0.63
4	0.13

The data in Table 2 obtained from the mine gave a temperature value (T) and pressure value (P) of 25°C and 2500 kPa, respectively. Substituting T and P_A in equation (6), the density of the exhaust air is then calculated as follows:

$$\rho = \frac{2{,}500{,}000\,\mathrm{Pa}}{278\,\mathrm{J/kg.K} \times 298.15\,\mathrm{K}}, \qquad \rho = 3.02\,\frac{\mathrm{kg}}{\mathrm{m^3}}. \tag{14}$$

Therefore, substituting the following results in equation (7), we have

$$\rho = 30.2\,\frac{\mathrm{kg}}{\mathrm{m^3}}, \qquad v = 7.67\,\frac{\mathrm{m}}{\mathrm{s}}, \qquad C_p = 59.3\%, \qquad A = \pi\frac{d^2}{4}, \tag{15}$$

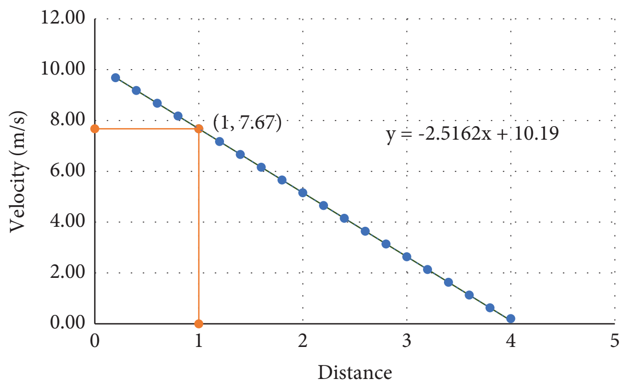


Figure 9: Mine exhaust wind frequency.

where d = 5 m and the theoretical wind power is calculated as follows:

$$P_{wT} = 0.593 \times \frac{1}{2} 30.2 \times \pi \times \frac{5^2}{4} \times 7.67^3,$$
$$P_{wT} = 79331.86 = 79.3\,\text{kW}. \tag{16}$$

The theoretical wind energy using equation (8) is also calculated as follows:

$$\text{wind energy} = P_{wT} \times t,$$
$$\text{wind energy} = 79.3\,\text{kW} \times 13\,\text{h}, \tag{17}$$
$$\text{wind energy} = 1031.31\,\text{kWh}.$$

Moreover, using the 70% efficiency of the ventilator vom fan, the realistic wind power can be calculated using the following equation:

$$\text{realistic wind power} = P_{wT} \times \text{ventilator efficiency},$$
$$\text{realistic wind power} = 79.3\,\text{kW} \times 0.70 \approx 55.51\,\text{kW}. \tag{18}$$

And the corresponding realistic energy recovered is calculated as follows:

$$\text{realistic energy recovered} = \text{realistic wind power} \times \text{time duration},$$
$$\text{realistic energy recovered} = 55.51\,\text{kW} \times 13\,\text{h} \approx 721.63\,\text{kWh}. \tag{19}$$

The calculations for theoretical wind energy and realistic wind power indicate that the wind energy recovery system at the studied mine has the potential to generate a significant amount of energy. The theoretical wind energy, estimated at 1031.31 kWh for a 13 h duration, represents the maximum wind energy that can be harnessed by the system. Considering the 70% efficiency of the ventilator vom fan, the realistic wind power that can be converted into usable electrical energy is calculated to be approximately 55.51 kW. This value reflects the actual power that can be extracted from the wind energy recovery system, taking into account the ventilator's efficiency. The corresponding realistic energy recovered from the wind energy recovery system, estimated at approximately 721.63 kWh for the given time duration, demonstrates the actual electrical energy generated by the system under realistic operating conditions.

Figure 10 presents a comparative analysis of energy recovery methods in the mining and mineral processing industry. The graph illustrates the energy values (MW) obtained from this study, and previous studies (Obracaj and Sas et al. [13], Fazlizan et al. [21], Xiong et al. [68], Bailey et al. [69], and Chong et al. [70]) that have explored various energy recovery techniques. Each point represents the energy value in megawatts (MW) recovered through different methods.

In the graph, we can observe that the studies have reported a range of energy values, with higher values obtained by some researchers, such as 47.5 MW [69], 11.05 MW [68], 9.5 MW [13], and 9–20 MW [71, 72]. However, our study's results show lower values, which can be attributed to the inefficiencies of specific wind turbine types used in the wind energy recovery system. The choice of wind turbine design and technology can significantly impact the system's overall efficiency and energy generation capacity. Moreover, interestingly, Chong et al.'s study [70] focused on recovering energy from cooling tower exhaust air for future green cities. Their system, utilizing two vertical-axis wind turbines, achieved a significant recovery of 13% of the energy required to power the fan motor in cooling towers, equivalent to 17.5 GWh/year or 199.5 kW.

Also, a study by Fazlizan et al. [21] showed that 1 kW (0.001 MW) of power could be produced using two VAWTs (side by side), which is significantly less than the value found in this study. While our study mainly focused on wind energy utilization in underground mining, the study by Fazlilan et al. focused on the application of VAWTs for energy recovery from cooling tower exhaust. Despite the differences between them, both studies share a common goal of improving energy efficiency and sustainability. By considering the insights from Fazlizan et al.'s research [21], we can further explore the feasibility of integrating VAWTs or other energy recovery technologies into our underground mine ventilation system. It opens up possibilities for diversifying our energy recovery methods and enhancing the overall energy efficiency of mining operations.

Even though these studies [13, 68–72] investigate energy recovery from diverse mining sites and industrial settings and consider different energy sources and efficiency aspects

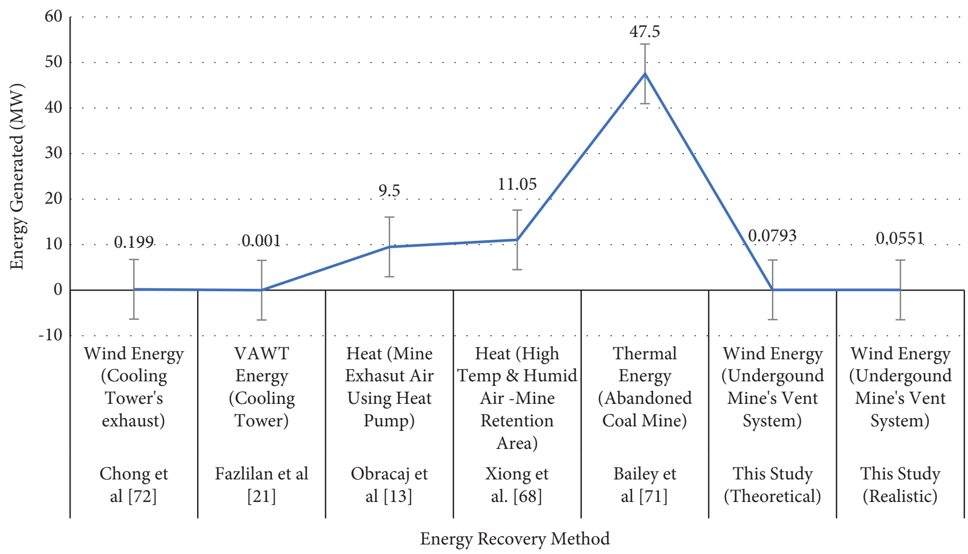


Figure 10: Comparative analysis of energy recovery methods in mining and mineral processing.

in their specific contexts, each approach has its unique merits and suitability for particular scenarios. While the mine's energy recovery potential may not be as high as some other operations [73], it is important to consider that each mining site is unique, and the wind energy recovery potential can vary based on factors such as location, wind resources, and the specific type of wind turbine used. In addition, the use of different energy recovery methods in mining and mineral processing can lead to varying energy generation capacities. Therefore, it is crucial to consider site-specific factors and conduct thorough assessments when implementing energy recovery strategies in different industrial settings.

This study's results further emphasize that the actual wind energy recovery is influenced not only by the wind speed and available wind power but also by the efficiency of the system (ventilator vom fan) converting wind power into usable electrical energy. Realistic calculations provide a more accurate representation of the energy that can be effectively harnessed from the wind resource and utilized for ventilation operations in the underground mine.

In addition, Table 1 shows that the installed capacity (P_{vt}) of the exhaust fan in the conventional ventilation system is 280 kW, with two fans operating simultaneously to ensure a conducive underground environment. The recoverable theoretical and realistic powers are calculated as follows:

$$\text{recoverable theoretical power (\%)} = \frac{79.3}{280} \times 100\% = 28\%,$$
$$\text{recoverable realistic power (\%)} = \frac{55.5}{280} \times 100\% = 19.8\%. \quad (20)$$

The calculated results underscore the potential for wind energy recovery in the underground mine ventilation system. The theoretical recoverable electricity is up to 28%, and under realistic conditions, up to 19.8% can be recovered, leading to corresponding energy savings of 200.7 kW and 224.5 kW, respectively. In comparison with Chong et al.'s study [70], which estimated that around 13% of the energy needed to power the fan motor in numerous cooling towers could be recovered using their system, the percentage of energy recovery in this approach is lower than that obtained herein. However, it is important to note that this approach is specifically tailored for applications in future green cities, offering valuable insights into harnessing wind resources for sustainable energy solutions.

Indeed, recovering 28% and 19.8% of the consumption capacity of the underground mine ventilation exhaust may not be sufficient for direct reutilization in the ventilation system. However, this opens up a new potential area for utilizing the recovered energy elsewhere in the mine operations. For instance, according to Andy [74], a mining site investigated had 75 W and 15 W bulbs installed, with a total of 2,000 bulbs throughout the mine. This means that the total power rating of the underground lighting system is a maximum of 75 W × 2,000 bulbs, which is equivalent to 150 kW. With the wind energy recovery system capable of producing up to 79.3 kW of wind power, it becomes evident that this recovered energy could be put to meaningful use in powering a significant portion of the underground lighting system. Considering the power consumption of the underground lighting system is approximately 150 kW [74, 75], the wind energy recovery potential of 79.3 kW represents a substantial portion of the required energy. This implies that nearly half of the power needed for the lighting system can be met by the recovered wind energy. Such an application presents a viable and practical way to reuse the energy and improve overall energy efficiency in the underground mine. By redirecting the wind energy to power critical components such as the underground lighting system, the mine can reduce its dependence on conventional electricity sources and further enhance its sustainability efforts [73, 75]. This approach not only maximizes the utilization of the recovered energy but also contributes to overall energy efficiency in the mining operations.

Furthermore, to enhance wind energy recovery efficiency and make the most of available wind power, the following measures can be considered:

(i) Upgrading the Ventilator vom Type fan system to a higher power capacity, allowing it to handle more wind power and capture a larger portion of the wind power

(ii) Exploring the use of multiple fans to increase the total power capacity and enhance the wind energy recovery process

(iii) Optimizing the system design to ensure maximum utilization of the available wind power within the fan system's capacity

Moreover, when comparing this study with other literature, Cabana et al. [35] investigated the potential of wind-driven power plants to meet a portion of the power demand in Ukrainian mining enterprises. However, they did not provide specific numerical values for wind energy potential or the recoverable power percentage, making their research less informative for evaluating wind energy utilization feasibility in mining operations. Similarly, De Souza [11] focused on ventilation system optimization without concrete data on energy generation, reducing its representativeness for assessing wind energy utilization feasibility in mining operations. While this study concentrates on wind energy recovery in underground mines, Chong et al.'s [29] work introduced a promising microwind turbine system without specific energy generation and efficiency metrics. Both studies offer valuable insights into energy recovery methods but target different applications, necessitating further assessment for practical implementation.

3.3. Estimation of Wind Energy Recovery: Methodology and Calculations. To estimate the wind energy recovery, we first measured the variation in wind velocity at different distances from the exhaust fans in the underground mine ventilation system. By analyzing the data, we identified a specific frequency at which the wind velocity increased as the distance from the fans increased. Based on this frequency, we predicted the change in wind speed at a distance of 1 m from the exhaust fan, which was found to be 7.67 m/s.

The wind energy formula was then used to calculate the potential wind energy recovery. We considered factors such as wind speed, turbine efficiency, and the energy demands of the ventilation system in our calculations. By applying these parameters to the formula, we estimated that a wind energy recovery system could theoretically recover 79.3 kW of the 280 kW consumed by the exhaust fan, representing respectively 28% of the energy used. Considering the 70% efficiency of the ventilator from the fan, the realistic wind power that can be converted into usable electrical energy is calculated to be approximately 55.51 kW, representing 19.8% of the energy used. The calculations for theoretical wind energy and realistic wind power indicate that the wind energy recovery system at the studied mine has the potential to generate a significant amount of energy. The theoretical wind energy, estimated at 1031.31 kWh for a 13 h duration, represents the maximum wind energy that can be harnessed by the system. This value reflects the actual power that can be extracted from the wind energy recovery system, taking into account the ventilator's efficiency. The corresponding realistic energy recovered from the wind energy recovery system, estimated at approximately 721.63 kWh for the given time duration, demonstrates the actual electrical energy generated by the system under realistic operating conditions. The contributions of this research lie in the accurate estimation of wind energy recovery from industrial exhaust air in the specific context of underground mine ventilation. By exploring the interactions between wind speed variations, turbine efficiency, and energy demands, we shed light on the realistic recoverable wind power. This information is vital for assessing the viability of wind energy utilization in mining operations, and it contributes to the growing body of knowledge in the field of renewable energy applications for industrial processes.

Overall, our study seeks to promote the development of sustainable energy solutions and to reduce the environmental impact of industrial processes. The results highlight the benefits of integrating renewable energy sources, such as wind energy, into underground mining operations, which can lead to cost reduction, enhanced energy efficiency, and a greener and more sustainable future for the industry.

3.4. Technical Challenges and Considerations for Wind Energy Recovery in Underground Mining. Implementing a wind energy recovery system in underground mining poses technical challenges and considerations [73]. Limited natural wind resources due to tunnels and structures can reduce available wind energy compared to surface locations. Unpredictable wind patterns can affect system efficiency [73, 76]. Integrating with the ventilation system requires ensuring smooth airflow and safety compliance. Careful turbine selection is crucial for maximum energy capture and durability in harsh conditions. Maintenance and accessibility in confined spaces are demanding. Energy storage is essential to manage intermittent wind energy production. Safety and regulatory compliance are paramount. Despite challenges, wind energy recovery offers cost reduction and environmental benefits with innovative technologies and thorough planning.

3.5. Economic Considerations for Evaluating Viability of Wind Energy Recovery in Underground Mine Ventilation Systems. Some of the economic factors to consider when implementing a wind energy recovery system in an underground mine ventilation system include upfront installation costs, covering equipment, labor, engineering, and permitting [77]. Ongoing maintenance expenses for inspections, repairs, and spare parts over the system's lifetime should also be taken into account. The system's ability to reduce energy costs by offsetting exhaust fan energy consumption with wind-generated electricity is crucial. Evaluating the payback period and return on investment (ROI) helps assess the time to recover the initial investment and the project's financial feasibility over its lifespan. Exploring government incentives, grants, tax credits, or power purchase agreements can further enhance the project's economic viability. Conducting a comprehensive economic analysis, including financial modeling with metrics such as net present value (NPV), internal rate of return (IRR), and sensitivity analysis, provides valuable insights into the project's profitability [77].

3.6. Environmental Sustainability: Emissions Reduction via Wind Energy Recovery in Underground Mines. Implementing a wind energy recovery system in an underground mine ventilation significantly contributes to environmental sustainability by reducing greenhouse gas emissions and other pollutants [78, 79]. Wind energy provides clean electricity, reducing reliance on fossil fuels and their associated emissions. The system also lowers fossil fuel consumption, leading to further greenhouse gas emission reduction [80]. By offsetting conventional power generation, the system helps reduce emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). In addition, it enhances air quality by replacing diesel-powered fans and reducing pollutants like nitrogen oxides (Nox), particulate matter, and sulfur dioxide [81]. Wind energy recovery aligns with sustainability goals and demonstrates a commitment to cleaner energy and carbon footprint reduction [79].

3.7. Limitations of the Research. The research acknowledges certain limitations that may affect the validity and applicability of its findings. Firstly, the study did not account for the sizing of a wind energy recovery system specific to the mine being examined. In addition, it did not delve into the specific characteristics of the turbine or the materials suitable for turbine construction, considering the presence of corrosive gases, dust, and other particles in the exhaust air, as well as the impact of environmental factors on the system. To fully deploy this empirically established concept, a comprehensive understanding of all the listed parameters is necessary. Future research and real-world implementations can address these limitations to further advance the utilization of wind energy recovery in underground mine ventilation systems.

4. Conclusion

We have successfully estimated the recoverable energy from the underground mine ventilation system exhaust through experimental support. Surprisingly, the optimal energy harvestable was not at the point closest to the exhaust, but slightly away from it, potentially from the experimental fan and the underground mine exhaust. The wind energy recovery system demonstrated the potential to generate a substantial amount of energy, with a theoretical estimation of 1031.31 kWh over a 13 h duration, approximately equivalent to 79.3 kW. Realistic calculations suggested a recoverable wind power of approximately 55.51 kW, leading to an estimated 721.63 kWh of recovered energy. While the wind energy recovery potential may not be as high as some other operations, it still highlights the significant potential for wind energy recovery in the underground mining sector. The recoverable power percentage of 28% theoretically and up to 19.8% realistically indicates the portion of electricity that could be recovered from the exhaust ventilation system. The wind energy recovery system has the potential to substantially contribute to the underground lighting system, providing nearly half of the required energy. To enhance efficiency, measures such as upgrading the fan system and optimizing the design should be considered. Overall, this study presents promising opportunities for wind energy recovery in the underground mining industry. Continued research and real-world implementations are essential to maximize energy savings and contribute to a greener and more sustainable future for the industry.

4.1. Recommendations. The following recommendations are made in light of the analysis and the findings obtained:

(i) Advanced turbine technologies that are better suited for the unique conditions of underground mines should be explored. High-efficiency turbines designed to withstand harsh and dusty environments can enhance the wind energy recovery system's performance.

(ii) Other potential areas for utilizing the recovered wind energy within the mining operations should be identified. Reusing the energy, such as powering lighting systems or other equipment, for other applications can further enhance energy efficiency and sustainability.

(iii) The computational fluid dynamic (CFD) approach should be used to further analyze the fluid flow so as to optimize the positioning of the turbine.

(iv) An efficient and cost analysis of the system should be conducted to determine its financial feasibility and performance of the system.

Data Availability

The data used in this study are available on request from the author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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