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Application of a Static System Weather Modification Technology for Rainfall Reduction in Coal Mining Areas

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ABSTRACT

Excessive rainfall poses a major challenge to coal mining operations by reducing operational time, limiting access to working areas, and disrupting the performance of heavy equipment. This study evaluated the effectiveness of a static Weather Modification Technology system using Ground Particle Generators (GPGs) in reducing rainfall intensity and duration. We tested the system in PT Borneo Indobara coal mining concession, South Kalimantan, Indonesia. Eight GPG units were deployed across the mining area from October 2021 to April 2022 during a La Niña period. Rainfall observations from Automatic Weather Stations (AWS), manual rain gauges, and satellite-based products were analyzed using both Target-Only and Target-Control approaches to assess the effectiveness of the intervention. Results showed that implementing GPG reduced rainfall intensity and rainfall duration by 51% and 77%, respectively, across the target mining areas. The reduction in rainfall substantially decreased weather-related operational disruptions. It contributed to an increase of 18.74 million tons in combined coal and overburden production between January and April 2022 compared to the same period in 2021. The findings demonstrate the potential of static GPG-based weather modification as an effective, cost-efficient approach to mitigating rainfall impacts in mining operations. The study provides scientific evidence for the broader application of weather modification technology to enhance operational resilience and productivity in weather-sensitive industries.

KEYWORDS

coal mining,weather modification technology; ground particle generator; rainfall reduction; mining productivity

1. INTRODUCTION

High rainfall poses significant challenges to coal mining operations, particularly in regions with pronounced rainy seasons. For example, PT. Borneo Indobara (PT. BIB) in South Kalimantan experienced significant disruption in mining activities due to heavy rainfall for 2021-2022, resulting in a substantial loss of time for PT. BIB. The heavy rain disturbances result in slippery mining roads, reduced visibility, and disruptions to heavy equipment operations, collectively leading to reduced operational time and limited work areas. As a result, the economic implications are profound, with lost time directly correlated with reduced coal production and profitability. Addressing these adverse influences is critical to optimizing mining productivity and ensuring economic sustainability. Weather modification technology (TMC) offers a promising solution to minimize disturbances caused by rainfall.

TMC encompasses a range of techniques that artificially influence atmospheric conditions to achieve desired weather outcomes. In general, weather modification technology to increase rainfall involves seeding clouds with hygroscopic materials. The purpose of TMC is to increase rainfall (Bahri et al., 2025), thereby maintaining the water levels of artificial dams, natural lakes, and reservoirs. This is crucial for supplying power generation and irrigation water needs, which in turn increase rice productivity levels during the dry season (Prasetio and Ashar, 2022; Sandhyavitri et al., 2023). Weather modification activities to increase the amount of rainfall can be carried out continuously if weather conditions are favorable, so that they can be used to maintain lake water levels, especially during the dry season (Prasetio et al., 2019)

A cloud seeding operational program carried out in sub-tropical region showed positive outcome by an increased rainfall of 10%-30% (Al Hosari et al., 2021). TMC has also been applied to reduce forest and land fires in Indonesia (Sandhyavitri et al., 2018; Sutikno et al., 2020; Tukiyat et al., 2022), including reducing transboundary haze (Sandhyavitri et al., 2020). TMC implementation is mainly carried out using aircraft, rockets, and ground-based generators (Abshaev et al., 2023; Bychkov et al., 2022; Renggono et al., 2022; Wan et al., 2023; Wondie, 2023; Yoo et al., 2022). This implementation highlights the role of TMCs in addressing diverse environmental, disaster, and industrial issues. However, the utilization of TMCs to reduce rainfall, especially in industrial contexts such as mining, remains largely unexplored. While hail suppression is a typical application of TMC in high-latitude countries (Givati and Rosenfeld, 2004; Petit et al., 2023; Rivera et al., 2020), rainfall reduction to increase industrial productivity is a new concept that requires intensive research. Recent studies in Indonesian coal mining areas have begun exploring ground-based CCN generators to suppress rainfall (Widodo et al., 2026).

The Indonesian government has recognized the usefulness of TMC, implementing it for various purposes, including ensuring safety during major sporting events such as the Sea Games in 2011 and the Islamic Solidarity Games in 2012, as well as flood mitigation in Jakarta during 2013 and 2014.

Based on this application, the current study aims to expand the use of TMC in the mining sector, specifically to reduce the Intensity and Duration of rainfall and minimize operational disruptions. This study addresses critical gaps in TMC implementation by exploring its potential to reduce rainfall in industrial environments, thereby increasing coal production and its economic impact. Utilizing TMC static systems with ground particle generators (GPGs) that use solution seeding material, the study pioneers a cost-effective and sustainable approach to weather modification, offers workable solutions for mining operations facing climate and weather challenges. The objective of study is to test the effectiveness of the TMC static system using GPG in reducing rainfall intensity and duration in mining areas.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted at the coal mining concession of PT Borneo Indobara (PT. BIB), located in Tanah Bumbu Regency, South Kalimantan, Indonesia (Figure 1a). The mining concession covers approximately 2,500 ha and comprises two major operational blocks, namely Kusan and Girimulya, which have been designated as target areas for weather modification activities. The region is characterized by a humid tropical climate with distinct wet and dry seasons (Sa'adi et al., 2021).

2.2 Experimental Design

A static TMC was implemented to reduce rainfall over the mining concession using eight Ground Particle Generator (GPG) units, which were distributed across the Kusan and Girimulya mining blocks (Figure 1b). The spatial distribution of the generators was designed to maximize coverage of the target mining area and enhance the effectiveness of hygroscopic seeding operations.

Each GPG unit consisted of a combustion chamber, a compressor, a seeding material solution tank, a water reservoir, and a liquefied petroleum gas (LPG) cylinder (Figure 1c). The generators released hygroscopic particles into the lower atmosphere, modifying cloud microphysical processes and suppressing rainfall development over the target area.

The GPG units were operated continuously from October 2021 to April 2022, with two daily operational shifts: 08:00–16:0 and 16:00–23:00 local time, totaling approximately 16 hours of operation per day. Throughout the operational period, rainfall conditions were monitored using Automatic Weather Stations (AWS) installed in both the target and control areas.

2.3 Datasets

The study utilized rainfall, meteorological, and mining production datasets to evaluate the effectiveness of TMC in reducing rainfall and improving mining productivity. Rainfall observations were collected from Automatic Weather Stations (AWS) installed within the target and control areas (Figure 1), complemented by manual rain gauge measurements for data validation. In addition, satellite-based precipitation products from the Tropical Rainfall Measuring Mission (TRMM) and Global Satellite Mapping of Precipitation (GSMaP) were used to support the spatial assessment of rainfall variability across the study area. Observed rainfall data from AWS were recorded at hourly intervals and subsequently aggregated for analyses of rainfall intensity and duration.

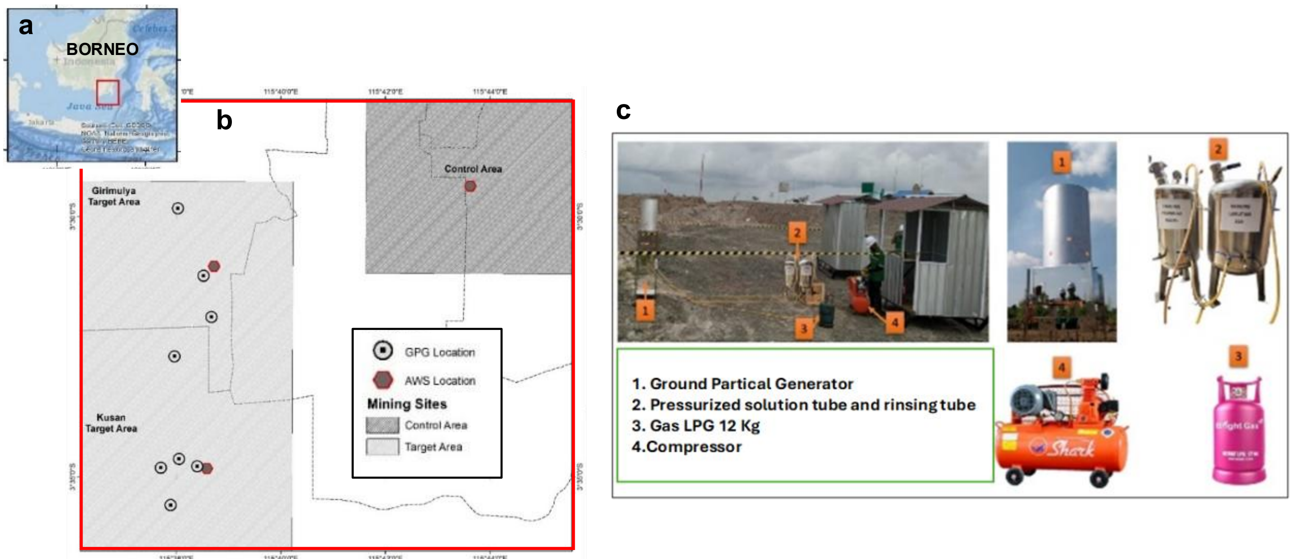

Figure 1. Study area and weather modification system. (a) Location of PT Borneo Indobara in South Kalimantan, Indonesia. (b) Distribution of target areas, control areas, AWS stations, and GPG units. (c) Ground Particle Generator (GPG) and its main components.

2.4 Datasets

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Weather variables measured by AWS included air temperature, relative humidity, atmospheric pressure, wind speed, and wind direction. These observations were used to characterize atmospheric conditions during the operational period and to evaluate the potential transport pathways of hygroscopic particles released by the Ground Particle Generators (GPGs). Further, operational records of coal and overburden (OB) production were obtained from PT Borneo Indobara to assess the indirect impacts of rainfall reduction on mining performance. A summary of the datasets used in this study is provided in Table 1.

2.5 Data Analysis

The effectiveness of TMC was evaluated based on changes in rainfall intensity and rainfall duration using both Target-Only and Target-Control approaches. Before the effectiveness assessment, the suitability of the control area was verified by correlating rainfall observations between the target and control areas. Following previous weather modification studies, a minimum correlation coefficient of 0.70 was adopted as the threshold for climatic similarity.

Table 1. List of datasets

Dataset	Source	Temporal Resolution
Rainfall	AWS	Hourly
	Manual rain gauge	Daily
	TRMM	3 Hourly
	GSMaP	Hourly
Meteorological variables	AWS	Hourly
Coal and OB production	PT BIB operational records	Monthly

In the Target-Only design, rainfall during the TMC operation was compared with historical rainfall from the same season. The percentage reduction in rainfall intensity or duration was calculated using Equation (1).

$$R = \frac{CH_s - CH_a}{CH_s} \times 100 \qquad (1)$$

where R is the rainfall reduction (%), CHa is the observed rainfall intensity (mm) or Duration (h) during GPG operation, and CHs is the corresponding historical rainfall intensity (mm) or Duration (h).

In the Target-Control design, rainfall conditions in the target area were compared with those observed in the control area during the same period. The rainfall reduction was calculated using Equation (2).

$$R = \frac{CH_c - CH_t}{CH_c} \times 100 \qquad (2)$$

where *CHt* represents rainfall intensity (mm) or Duration (h) in the target area, and *CHc* represents rainfall intensity (mm) or duration (h) in the control area.

To determine whether rainfall characteristics differed significantly between the target and control areas, statistical analyses were performed in R at the 95% confidence level. Finally, the operational benefits of rainfall reduction were assessed by comparing coal and overburden production during the weather modification period (January – April 2022) with production during the corresponding period in the previous year (January – April 2021). This comparison was used to quantify the contribution of rainfall reduction to improvements in mining productivity.

3. RESULTS AND DISCUSSION

3.1 Rainfall patterns in the target area

Understanding rainfall variability is essential for evaluating the effectiveness of TMC operations. The study area, comprising the Kusan and Girimulya mining blocks, experienced wetter-than-normal conditions during the 2021–2022 wet season due to a moderate-to-strong La Niña event. Figure 2 shows the monthly rainfall distribution during the study period compared with the historical climatology (2009–2017). The rainy season generally extends from November to June, while July to October represents the transition from the dry to wet season.

During La Niña, rainfall is substantially higher than the normal average, particularly during the dry season and transition months. Compared with the historical mean, monthly rainfall increased by 46 mm in May, 181 mm in June, 115 mm in July, 450 mm in August, and 368 mm in September. The most pronounced anomaly occurred in August and September, when rainfall reached 524 mm (+ 600%) and 460 mm (+400%), respectively. These results indicate that the dry season was considerably wetter than usual, reflecting the strong influence of La Niña on regional rainfall patterns.

Overall, cumulative rainfall during the study period reached 4,468 mm (+30% from normal year). This substantial positive anomaly confirms that mining operations were conducted under exceptionally wet conditions. Such conditions typically increase the frequency of operational disruptions, including reduced visibility, slippery haul roads, localized flooding, and delays in excavation and transportation activities. Therefore, the study period provided a rigorous test of the effectiveness of TMC, as rainfall suppression efforts were implemented during a season characterized by above-normal precipitation.

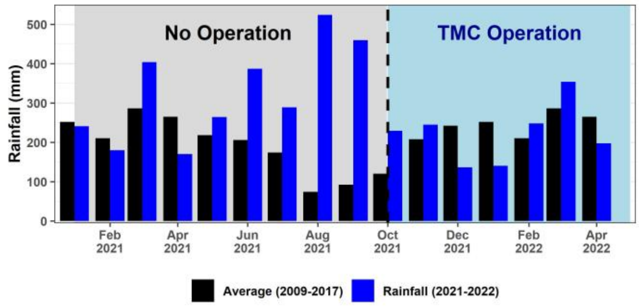

Figure 2. Comparison of monthly rainfall (2021–2022) and historical mean (2009–2017) in the study area before and during the TMC operation.

3.2 Effectiveness of TMC in Reducing Rainfall

To evaluate whether TMC operations mitigated the exceptionally wet conditions associated with La Niña, rainfall intensity and duration data from the target and control areas were analyzed using both Target-Only and Target-Control approaches. Statistical analyses conducted at the 95% confidence level revealed significant differences in rainfall characteristics between the treated and untreated areas, indicating that the observed changes were unlikely to be solely attributable to natural climate variability.

The primary objective of the TMC operation was to suppress rainfall development and reduce weather-related disruptions to mining activities. Across both mining blocks, rainfall intensity decreased by 45–55%, while rainfall duration decreased by 73–80% (Figure 3). In the Kusan block, rainfall intensity decreased by 45–49%, and rainfall duration decreased by 73–77%. Slightly greater reductions were observed in the Girimulya block, where rainfall intensity decreased by 53–55% and rainfall duration by 78–80%.

The findings obtained from the Target-Only and Target-Control evaluations demonstrates the robustness of the observed rainfall suppression effect. The implementation of TMC using Ground Particle Generators (GPGs) resulted in the reduction of mean rainfall intensity and duration by 51% and 77%, respectively, across the target mining areas (Figure 3). These findings indicate that the static GPG-based weather modification system was effective in suppressing rainfall development even under unusually wet climatic conditions.

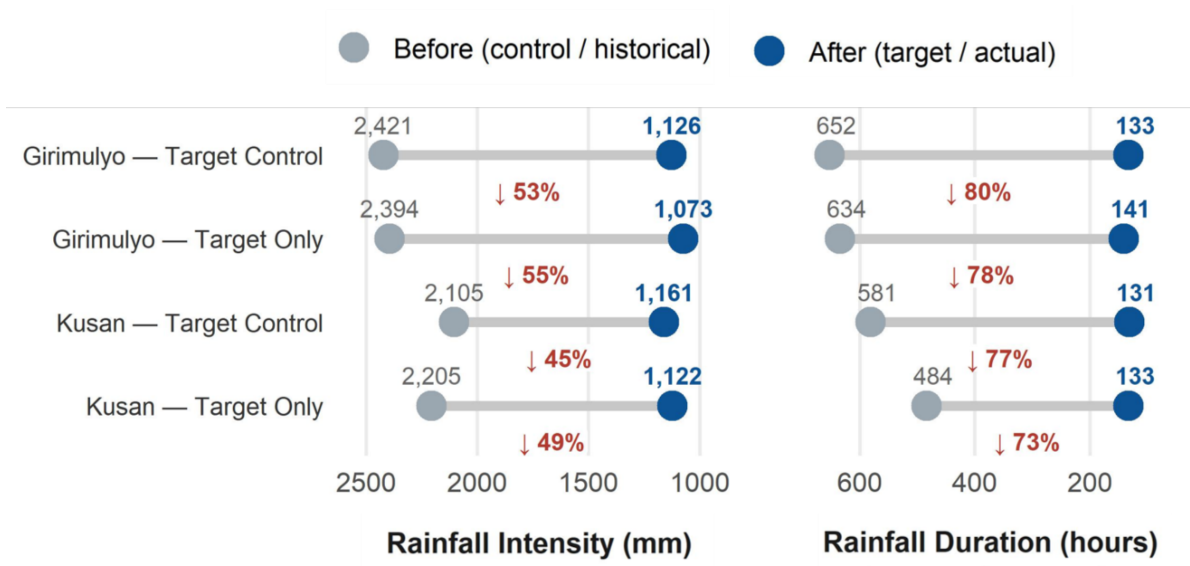

Figure 3. Changes in rainfall intensity and Duration following weather modification operations in the Kusan and Girimulyo mining blocks.

3.3 Implications for Mining Operations

The substantial reduction in rainfall intensity and Duration observed during TMC operations (Figure 3) provided direct operational benefits for mining activities. Before TMC implementation, PT Borneo Indobara experienced monthly operational downtime ranging from 36.83 to 138.61 hours due to rainfall-related disruptions. As summarized in Table 2, combined coal and overburden (OB) production increased from 46.90 million tonnes/bcm during January–April 2021 to 65.64 million tonnes/bcm during the same period in 2022, representing an additional 18.74 million tonnes/bcm of mining output. Although coal production remained relatively stable, overburden removal increased substantially by 19.82 million bcm, indicating improved equipment utilization and operational efficiency during the TMC period.

These findings suggest that rainfall suppression can generate significant economic and operational benefits in weather-sensitive mining environments. The observed improvements are consistent with previous studies demonstrating that weather modification technologies can alter precipitation processes and reduce weather-related impacts. While most TMC applications have focused on rainfall enhancement, typically increasing precipitation by 10–40% (Al Hosari et al., 2021; Bahri et al., 2025), the present study demonstrates the potential of TMC for rainfall suppression under tropical conditions.

The effectiveness observed in this study aligns with core cloud microphysics principles, where introducing elevated aerosol concentrations can suppress precipitation by modifying cloud microphysical processes and delaying raindrop formation. In an industrial context, these results strongly align with a previous ground-based weather modification study in an Indonesian coal-mining environment, which demonstrated that static Ground Particle Generator (GPG) operations significantly boosted cloud condensation nuclei (CCN) concentrations by 312%, thereby successfully inhibiting droplet growth and delaying rainfall onset (Widodo et al., 2026).

Despite being conducted during a wetter-than-normal La Niña period, when cumulative rainfall exceeded the historical climatological average by approximately 33% (Figure 2), the GPG-based TMC system successfully reduced both rainfall intensity and duration (Figure 3) while simultaneously improving mining productivity (Table 2). This breakthrough highlights the potential of static weather modification systems as an effective operational strategy for mitigating rainfall-related risks and enhancing productivity in tropical open-pit mining operations.

4. CONCLUSION

The implementation of GPG resulted in the reduction of rainfall intensity and duration by 51% and 77%, respectively across the Kusan and Girimulya mining blocks. The reduction in rainfall is directly correlated with a decrease in lost operational time, which means an increase in production of 18.74 million tonnes between January and April 2022 compared to the same period in 2021. This increase underscores the effectiveness of TMCs in improving mining operations during high rainfall conditions. The surge in coal production and overcoat (OB) not only increases the company's revenue but also contributes positively to the local and national economy by ensuring a stable supply of energy resources. The cost-effectiveness of the TMC static system, which is less expensive than dynamic aircraft-based systems, further underscores its

Table 2. Comparison of Mining Production Before and During Weather Modification Operations (TMC)

Period	Rainfall Condition	Coal Production (Mt)	OB Production (M bcm)	Total Production
Jan–Apr 2021 (Pre-TMC)	Wet season	10.49	36.41	46.9
Jan–Apr 2022 (TMC)	Wet season (La Niña)	9.41	56.23	65.64
Difference	–	-1.08	19.82	18.74

economic feasibility for sustainable mining industry applications. These findings unequivocally show that implementing TMC in a static system with GPG effectively reduces rainfall intensity and Duration and increases mining productivity.

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