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Review Article

Assessing the Economic Viability of Fertilizer Production through Petcoke-Fired Boiler Flue Gas Utilization in An Indian Chemical Complex: A Feasibility Study

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Abstract - *This research investigates the feasibility of producing ammonium sulfate fertilizer from waste flue gas in a chemical complex setting. The analysis reveals promising results, indicating potential avenues for optimization and scale-up of conversion processes. Emphasis is placed on the scalability of production facilities and the need for comprehensive life cycle assessments to evaluate environmental impacts and sustainability. Additionally, the study recommends the adoption of Ammonia-based WFGD systems for effective SO_2 emission control, aligning with environmental compliance and sustainable industrial practices. The economic potential of ammonium sulfate production as a byproduct underscores its significance in both environmental stewardship and revenue generation. Overall, the findings highlight opportunities for enhancing economic sustainability while ensuring environmental responsibility in industrial operations. Further research and strategic planning are warranted to maximize the benefits of utilizing waste flue gases for fertilizer production, thus contributing to the advancement of sustainable industrial practices.*

Keywords - *Waste flue gas, Ammonium sulfate fertilizer, Sustainability.*

1. Introduction

Nirma Chemicals Limited,[12] situated near Kalatalav village in Bhavnagar District, Gujarat State, conducted a feasibility study to assess the economic viability of fertilizer production using petcoke-fired boiler flue gas. The chemical complex spans over 35,000 hectares and employs over 1200 individuals across various departments. The complex houses need essential facilities like engineering buildings, health and safety departments, canteens, hostels, and guest houses. Notable production units include limekiln, power plant, caustic plant, and bagging units. The utility section operates a 164 MW cogeneration unit with six boilers, including models from Lentjes Germany and Isgec John Thomson India Limited, ranging in capacity from 100 to 410 TPH. This study explores the potential of utilizing boiler flue gas for fertilizer production, aiming to enhance economic viability and sustainability within the complex. The configuration of the boiler system at the Chemical Complex is depicted in Figure 4.

The deleterious effects of Sulfur Dioxide (SO_2) emissions from industrial waste flue gas on the environment, human health, and ecosystems have long been acknowledged as a serious problem. Industrial operations, such as electricity generation, metal smelting, and chemical manufacturing, significantly contribute to the emission of sulfur dioxide into the atmosphere, leading to many negative consequences. An important concern related to sulfur dioxide emissions is its contribution to air pollution and the creation of acid rain. When sulfur dioxide comes into contact with moisture in the air, it changes into sulfuric acid, which then falls to the ground as precipitation. Acid rain causes harm to structures, infrastructure, and plants. It poses a danger to aquatic ecosystems by making lakes, rivers, and streams more acidic, which has a negative impact on aquatic organisms.

In addition, sulfur dioxide emissions are associated with the formation of fine Particulate Matter (PM2.5) and ground-level ozone, both of which are connected to respiratory and cardiovascular health issues in humans. Sulfur dioxide exposure may exacerbate respiratory ailments, including asthma and bronchitis, especially impacting susceptible groups such as children, the elderly, and persons with pre-existing health disorders. Sulfur dioxide emissions have a substantial influence on global climate change, in addition to their direct effects on human health and the environment. Sulfur dioxide may serve as a precursor to sulfate aerosols in the atmosphere, which can reflect sunlight and decrease the amount of solar radiation that reaches the Earth's surface, resulting in a cooling impact. Nevertheless, the existence of sulfate aerosols also plays a role in regional climatic fluctuations and participates in intricate interactions with other greenhouse gases.

Given the extensive environmental dangers caused by sulfur dioxide emissions from industrial waste flue gas, there is a pressing want for inventive and sustainable methods to reduce these detrimental impacts. This research aims to assess the feasibility of converting waste flue gas, which contains sulfur dioxide, into valuable commodities, such as ammonium sulfate fertilizer. This concept presents a potential approach to not only reduce emissions but also enhance the retrieval of resources and enhance environmental sustainability.

The study aims to explore the economic viability and sustainability of this approach within the complex, addressing a critical research gap in finding inventive and sustainable solutions to mitigate the deleterious effects of Sulfur Dioxide (SO_2) emissions from industrial waste flue gas. These emissions contribute significantly to air pollution, acid rain formation, and health issues, highlighting the urgent need for innovative methods to reduce these impacts. This study focuses on transforming waste flue gas containing sulfur dioxide into valuable commodities like ammonium sulfate fertilizer, offering a potential solution to both emission reduction and resource recovery while enhancing environmental sustainability.

2. Literature Review

2.1. Background on Sulfur Dioxide Emissions

Multiple studies emphasize the urgent need to address Sulfur Dioxide (SO_2) emissions due to their detrimental effects on the environment and human health. Industrial operations, such as electricity generation and chemical manufacturing, are significant contributors to SO_2 emissions, leading to air pollution, acid rain formation, and respiratory health issues.

Multiple studies emphasize the immediate need for efficient measures to tackle sulfur dioxide emissions and their related effects. Authors [1] emphasized the connection between industrial operations and elevated levels of sulfur dioxide in the atmosphere, underscoring the need for strict emission control measures. In their study, Authors [2] examined the negative impacts of acid rain on ecosystems and highlighted the need to investigate novel strategies to reduce sulfur dioxide.

The literature has examined the prospect of transforming sulfur dioxide emissions into useful goods. In their study, authors [3] examined the practicality of converting sulfur dioxide into ammonium sulfate fertilizer, which offers a potential solution for reducing waste and recovering valuable resources. Authors [4] conducted a review of the latest developments in catalytic procedures for converting sulfur dioxide. Their study highlighted possible improvements in sustainable waste management.

The urgency to address Sulfur Dioxide (SO_2) emissions and their environmental impacts has led to a wealth of research exploring various aspects of mitigation strategies. In a comprehensive analysis, Authors [5] investigated the role of catalytic technologies in reducing sulfur dioxide emissions, emphasizing the potential for these technologies to enhance efficiency in industrial processes. This aligns with the overarching objective of our study to explore innovative methods for sulfur dioxide conversion.

Sulfur dioxide emissions have environmental implications that go beyond local and regional dimensions. In their study, Authors [6] performed a comprehensive evaluation of the effects of sulfur dioxide on the climate at a global scale. They emphasized the interdependence between emissions and their role in influencing wider patterns of climate change. Gaining a comprehensive understanding of these worldwide consequences is essential for creating long-lasting solutions that effectively tackle both local and global issues.

Authors [7] conducted research in the field of sustainable agriculture, specifically investigating the advantages of using ammonium sulfate fertilizer produced from sulfur dioxide emissions. Their research emphasized both the effectiveness of ammonium sulfate in improving agricultural yields and its contribution to reducing environmental pollution. This highlights the two-fold advantages that may be obtained by transforming waste flue gas into useful agricultural resources. The study conducted by authors [8] provides a thorough examination of the latest methods and catalysts used in the conversion of sulfur dioxide, offering valuable insights into technical progress in this field. This information is crucial in directing our investigation of viable and effective conversion methods in the context of producing fertilizer from waste flue gas.

Catalytic conversion processes offer a sustainable solution for reducing Sulfur Dioxide (SO_2) emissions, transforming them into valuable elemental sulfur. Transition metal-based catalysts, like copper-alumina and nickel-alumina, achieve near-complete SO_2 conversion with high selectivity for sulfur. Advanced catalysts, such as Al_2O_3-Cu, demonstrate exceptional performance, achieving a 99.9% SO_2 conversion rate and 99.5% sulfur selectivity at optimal conditions. By utilizing catalytic reduction, SO_2 emissions can be effectively mitigated while producing valuable elemental sulfur, making it an environmentally friendly approach to address air pollution concerns [14, 15]

The present study aims to add to the existing knowledge on mitigating sulfur dioxide emissions by using these findings.

The emphasis on transforming waste flue gas into ammonium sulfate fertilizer is in line with the overarching objective of promoting sustainable practices in industrial operations, addressing environmental issues and encouraging the efficient use of resources. The primary objective of this research is to contribute to the current understanding of reducing sulfur dioxide emissions by using these discoveries. The focus on converting waste flue gas into ammonium sulfate fertilizer aligns with the primary goal of supporting sustainable practices in industrial operations, addressing environmental concerns and boosting resource efficiency.

The novelty of this work lies in its specific focus on the economic viability and practical implementation of producing fertilizer from petcoke-fired boiler flue gas within an Indian chemical complex. While existing research has explored the conversion of sulfur dioxide emissions into useful commodities like ammonium sulfate fertilizer, our study uniquely addresses the challenges and potentials of this process within the context of Indian industrial settings.

Comparing this research with existing findings, prior studies have largely examined the technical aspects and environmental benefits of sulfur dioxide conversion, emphasizing the importance of emission reduction and resource recovery. However, this study goes beyond by explicitly evaluating the economic feasibility and practical implementation of such a process within a specific industrial complex in India. Additionally, while some studies have explored the global and regional impacts of sulfur dioxide emissions on climate and ecosystems, our research focuses on localized solutions tailored to the needs and constraints of the Indian industrial environment.

By concentrating on the economic viability and feasibility of fertilizer production from waste flue gas, this study provides practical insights and recommendations that address the unique challenges and opportunities of the Indian industrial landscape. This distinct approach contributes to the advancement of knowledge on mitigating sulfur dioxide emissions while promoting sustainable practices and resource efficiency in industrial operations.

3. Materials and Methods

3.1. Ammonia-based Scrubbing Process Overview: A Detailed Examination

Scrubbing technology that is based on ammonia is now widely acknowledged as a significant alternative for reducing the amount of Sulfur Dioxide (SO_2) emissions that coal-fired power stations produce via their flue gas effluent. In this section, a comprehensive analysis of the technology, with a specific emphasis on major suppliers in the United States and a thorough explanation of the process

3.2. Ammonia-Based Scrubbing Technology Suppliers

Marsulex Environmental Technologies (MET) and Jiangnan Environmental Technology (JET) are major players in Flue Gas Desulfurization (FGD), employing ammonia-based scrubbing methods. MET, with over 150 systems globally, focuses on diverse FGD techniques and has had a long-standing presence since its inception in the 1990s. JET, a subsidiary of JNEP, dominates the Chinese market with over 300 installations of their Efficient Ammonia Desulfurization (EADS) system, particularly targeting coal-fired units. Both companies continue to innovate, with MET's recent project in Louisiana and JET's ultrasonic enhancements in their latest EADS generation showcasing their commitment to reducing sulfur emissions worldwide [13].

Aside from supplier details, understanding the process behind ammonia-based cleaning technology is essential for assessing its effectiveness. The core procedure involves the assimilation of sulfur dioxide from flue gas by injecting ammonia into an absorber tower. These reactants combine to produce ammonium sulfite and ammonium bisulfite, which are then converted into ammonium sulfate by oxidation. The ammonium sulfate fertilizer produced as a byproduct has the potential for sustainable resource recovery.

In addition, there have been recent developments in ammonia-based scrubbing that include the use of ultrasound to increase the removal of Sulfur Oxides (deSOX) and Particulate Matter (PM), as shown in JET's 4th generation EADS system. This invention seeks to improve the overall efficiency of the desulfurization process while also addressing problems related to particle matter.

3.3. Basic Process Flow

The first step involves channeling flue gas from a particle control device towards the base of an absorber tower. Internally, the gas encounters a fully saturated mixture of ammonium sulfate, resulting in a decrease in temperature and an improvement in the interaction between the gas and liquid phases. The interaction between the slurry and the gas heat causes water to evaporate, resulting in the formation of useful sulfate of ammonium crystals as a byproduct. The chemical reactions involved include the absorption of SO_2 into water, subsequent reactions forming ammonium bisulfite and sulfate species, and oxidation to produce ammonium sulfate [9].

$$SO_2 + 2NH_3 + H_2O = (NH_4)2SO_3 \quad (1)$$

$$(NH_4)2SO_3 + \frac{1}{2} O_2 = (NH_4)2SO_4 \quad (2)$$

The chemical equation represents the reaction of Sulfur Dioxide (SO_2) with ammonia (NH_3) and water (H_2O) to form ammonium sulfite $(NH_4)2SO_3$. The subsequent reaction of ammonium sulfite with half of an oxygen molecule (1/2 O_2) results in the formation of ammonium sulfate $(NH_4)2SO_4$.

3.3.1. Scrubbed Flue Gas Treatment

After the absorption process, the cleaned flue gas leaves the top of the absorber and undergoes further treatment to eliminate any liquid droplets and particles that may still be present. This purified gas is then exhausted through a chimney or stack.

3.3.2. Reaction Tank and Slurry Processing

The ammonium sulfate slurry descends to a reaction tank, where oxidation air and ammonia are introduced. The resulting reaction tank slurry, consisting of ammonium sulfate solids and various liquid-phase components, is recirculated to the absorber tower. This slurry serves as the foundation for further processing into ammonium fertilizer products.

3.3.3. Fertilizer Production

Ammonia-based scrubbers are intended to produce three primary sorts of products: a diluted slurry, a conventional crystalline structure, and a compacted hard granular product. The batch-mode operation allows for periodic processing of a slurry bleed stream into fertilizer. For solid ammonium sulfate fertilizer, a dewatering process involving hydrocyclones and centrifuges is employed. The solids are subsequently dried, and the resulting product can be either a standard crystal or a granular form. The latter requires additional equipment, such as conveyors and hammer mills, incurring substantial capital investment.

3.3.4. Slurry Liquid Phase Management

In handling the liquid phase of the slurry, they are primarily composed of captured fly ash; both MET and JET utilize a combination of hydrocyclones, centrifuges, and filter presses. MET consistently incorporates a filter press into its design, whereas JET employs it selectively, contingent upon the efficiency of upstream particulate control. The extracted moisture is then either reintroduced into the absorber or sprayed onto the ammonium sulfate product during the drying process.

3.3.5. Process Water Management

Water used in the process, including that lost through evaporation, is stored in a dedicated tank and replenished to compensate for losses. This ensures the sustainability and continuous operation of the ammonia-based scrubbing process.

3.4. Economic Analysis of Ammonia-Based Scrubbing Technology

To conduct a comprehensive economic analysis of ammonia-based scrubbing technology, it is necessary to evaluate many crucial elements carefully. Trimeric performed an initial evaluation, specifically examining the sulfur content of coal, the availability and pricing of ammonia, the local market for ammonium sulfate, the possibility of reusing or modifying current infrastructure, the need for new infrastructure, transportation logistics, return-on-investment models, and other pertinent factors. Although this paper does not provide a detailed economic analysis, it does include a brief overview of important results and factors to consider. Finally, producing ammonium sulfate fertilizer from sulfur dioxide in boiler flue gas using wet gas scrubbing technology necessitates a comprehensive assessment of costs, revenue, profitability, risks, and feasibility. Thorough planning, market research, and financial modeling are essential for project success.

3.5. Coal Sulfur Content

The sulfur content in coal significantly influences the rate of production of ammonium sulfate fertilizer, particularly in larger power plants. Coals with higher sulfur content, typically 2% or more, can enhance the economic viability of ammonia scrubbers, which are crucial for sulfur dioxide elimination. Using coal with higher sulfur content than currently employed by Vectren could yield financial benefits. Similarly, in petroleum coke, sulfur content plays a vital role in determining its quality and environmental impact. Excessive sulfur levels may result in heightened emissions of sulfur dioxide upon combustion, hence contributing to the occurrence of pollutants in the air and precipitation of acid rain. Monitoring and controlling sulfur content in petroleum coke is essential to meet environmental regulations and maintain fuel quality. Commonly used techniques for measuring sulfur concentration in petroleum coke include fluorescence from X-ray spectroscopy, inductively connected plasma spectroscopy, and ignition analysis. [9, 10, 11, 13].

3.6. Ammonia Availability and Pricing

Regional Market for Ammonium Sulfate: The economic viability of the ammonia-based scrubbing method depends on the accessibility of ammonia at a competitive cost. Although A.B. Brown does not produce ammonia on-site, it nonetheless benefits from substantial ammonium sulfate generation, even though most MET installations have ammonia readily available on-site. The yearly demand for anhydrous ammonia, assuming a 52% utilization rate, is around 40,000 short tons. This represents just a portion of the total ammonia production capacity in the United States.

The price of anhydrous ammonia may range from $300 to $375 per ton, whereas ammonium sulfate can range from $100 to $280 per ton. These variances are influenced by the distances involved in shipping and the dynamics of the market. It is advisable to do thorough economic research by professionals who are knowledgeable about the local markets in order to verify these numbers for A.B. Brown.

To get a comprehensive knowledge of prospective product margins, Trimeric analyzed cost and revenue streams for three alternative scenarios, each based on varying assumptions on the costs of ammonia and fertilizer. These scenarios demonstrated a possible yearly profit margin that varied from reaching a balance point to $27 million, depending on the variables taken into account. When doing a thorough study, it is crucial to take into account aspects such as the environmental consequences, adherence to regulations, and improvements in ammonia-based scrubbing technology. These factors may have a substantial impact on the overall economic environment. The balanced chemical equation for the reaction between sulphur dioxide, ammonia, Oxygen, and water to produce ammonium sulphate is:

$$2SO2 + 4NH3 + O2 + 2H2O \rightarrow 2(NH4)2SO4 \quad (3)$$

4. Results and Discussion

Based on the provided summary and discussion, the results demonstrate a clear relationship between steam generation capacity, fuel characteristics, and SOx emissions in boilers using petcoke as a fuel source. Here is a structured summary:

4.1. Fuel Characteristics

Petcoke with a sulfur content ranging from 5.0% to 7.0% on a weight basis. The available steam fuel ratio is approximately 6.5.

4.2. Steam Generation Data

Three scenarios were considered for different steam generation capacities: 600 TPH (100% MCR), 500 TPH, and 450 TPH, along with two future scope scenarios of 1000 TPH and 800 TPH.

4.3. Sulfur Content and SOx Generation

The weight of sulfur in the fuel is calculated based on the fuel's sulfur content. SOx generated due to excess air is calculated for each scenario.

4.4. Discussion

As steam generation decreases, both the amount of fuel required and the weight of sulfur in the fuel decrease proportionally. SOx generation due to excess air follows a similar trend, decreasing with lower steam generation capacities.

The chemical balance aspect is emphasized, showing the relationship between sulfur and Oxygen in the combustion process. The chemical equation S (32) + O_2 (32) = SO_2 (64) is highlighted, indicating the requirement of one ton of Oxygen to produce two tons of Sulfur Dioxide (SO_2).

In summary, the results underscore the importance of understanding the interconnections between steam generation capacity, fuel consumption, sulfur content, and SOx emissions. This understanding is vital for optimizing operational efficiency and minimizing environmental impact in chemical complexes utilizing petcoke as a fuel source.

The data from Table 2 depicting the calculations for the Ammonia-based Wet Flue Gas Desulfurization (WFGD) system for Nirma reveals a systematic correlation between the removal capacity of Sulphur Dioxide (SO_2) and the necessary amounts of ammonia, water, and Oxygen. As the SO_2 availability increases from 1 TPH to 20 TPH, the corresponding ammonia, water, and Oxygen requirements show a proportional growth. The resulting ammonium sulfate production also follows this trend, demonstrating the direct impact of SO_2 removal on the output of the desulfurization process. The table emphasizes the resource demands and product yields at various operational scales.

The calculations highlight the efficiency of the Ammonia-based WFGD system in addressing SO_2 emissions. Notably, the ammonia requirement for SO_2 removal rises from 0.53125 TPH at 1 TPH SO_2 availability to 10.625 TPH at 20 TPH SO_2 availability. Similarly, water and Oxygen needs increase proportionally. The resulting production of ammonium sulfate, a valuable byproduct, indicates the system's efficacy in converting SO_2 into a useful material. The scaling relationship observed in the table is crucial for process optimization, allowing for informed decision-making in system design and operation.

Table 3 presents the potential revenue generation from waste flue gases under both MET and JET scenarios, considering varying sulfur dioxide availabilities measured in Tons Per Hour (TPH). In the MET scenario, revenue generation increases progressively with sulfur dioxide availability, with a notable exponential growth pattern. For instance, revenue starts at 274,492,683.8 INR per year for 1 TPH of sulfur dioxide and doubles with each increment, reaching 5,489,853,675 INR per year for 20 TPH.

This signifies significant economic potential in scenarios with ample sulfur dioxide availability. On the other hand, in the JET scenario, revenue generation also correlates positively with sulfur dioxide availability. However, it follows a linear growth trajectory with smaller increments compared to the MET scenario. The revenue increases steadily with each additional ton of sulfur dioxide, reaching 1,726,694,550 INR per year for 20 TPH.

While the growth is not as pronounced as in the MET scenario, there is still a positive correlation between sulfur dioxide availability and revenue generation, indicating economic viability in utilizing this resource. According to the chemical balance, 1 ton of Sulphur requires 1 ton of Oxygen to produce 2 tons of Sulphur Dioxide. The equation represents this:

$$S (32) + O2 (32) = SO2 (64) \quad (4)$$

Figure 1 compares steam generation parameters and environmental impact across scenarios. "Future Scope (1000 TPH)" has the highest steam generation at 1000 TPH, requiring 153.85 TPH of fuel with sulfur content ranging from 7.69 to 10.77 TPH. It also generates the most SOx emissions at 15.38 to 21.54 TPH. Conversely, "Current condition (450

TPH)" has the lowest values across these metrics, indicating variations in efficiency and environmental impact. The bar chart, represented in Figure 2, illustrates the production scale-up of ammonium sulfate through chemical reaction parameters.

The x-axis represents different scales of sulfur dioxide availability, ranging from 1 to 20 Tons Per Hour (TPH). The y-axis depicts the corresponding values for ammonia required (TPH), water required (TPH), Oxygen required (TPH), ammonium sulfate product (TPH), and production (TPD). Each bar represents a specific scale of sulfur dioxide availability, showcasing the relationship between the input parameters and the resulting production of ammonium sulfate. Figure 3 depicts a comparison of revenue generation scope between the MET and JET scenarios based on different levels of sulfur dioxide availability. The x-axis represents the sulfur dioxide availability in Tons Per Hour (TPH), while the y-axis illustrates the revenue generation scope in Indian Rupees (INR) per year. Each bar corresponds to a specific sulfur dioxide availability level, showcasing the revenue potential under both the MET and JET scenarios. The chart highlights the impact of sulfur dioxide availability on revenue generation, providing valuable insights for decision-making processes.

Table 1. Sulfur dioxide availability from boilers utilizing petcoke as fuel

Fuel	Sulphur % on Weight Basis (Min. -Max.) LAB Data	Available Steam Fuel Ratio w.r.t. Fuel (DCS Panel)	Steam Generation (TPH DCS PAnel)	Amount of Fuel Required for Steam Generation (TPH)	Weight of Sulphur in Fuel Amount (TPH) (Min. - Max.)	SOx Generated Due to Excess Air (TPH) (Min. -Max.)
For all boilers on 100% MCR						
Petcoke	5.0 - 7.0	6.5	600	92.31	4.61 - 6.46	9.22 - 12.92
For a total steam generation, 500 TPH						
Petcoke	5.0 - 7.0	6.5	500	76.92	3.84 - 5.38	7.68 - 10.76
For current condition, i.e. 450 TPH steam generation						
Petcoke	5.0 - 7.0	6.5	450	69.23	3.46 - 4.84	6.92 - 9.68
For future Scope						
Petcoke	5.0 - 7.0	6.5	1000	153.85	7.69 - 10.77	15.38 - 21.54
For future Scope						
Petcoke	5.0 - 7.0	6.5	800	123.08	6.15 - 8.61	12.30 - 17.22

Table 2. Calculation of wet flue gas desulfurization efficiency using ammonia-based system

Sulphur Dioxide Availability (TPH)	Ammonia Required (TPH)	Water Required (TPH)	Oxygen Required (TPH)	Ammonium Sulphate (TPH) Product	Production (TPD)
SO_2	$2NH_3$	H_2O	$0.5O_2$	$(NH_4)2SO_4$	
Chemical Balance	0.000034	0.000018	0.000016	0.00132	
1	0.53125	0.2813	0.25	2.063	49.50
2	1.0625	0.5625	0.50	4.125	99.00
3	1.59375	0.8438	0.75	6.188	148.50
4	2.125	1.1250	1.00	8.250	198.00
5	2.65625	1.4063	1.25	10.313	247.50
10	5.3125	2.8125	2.50	20.625	495.00
15	7.96875	4.2188	3.75	30.938	742.50
20	10.625	5.6250	5.00	41.250	990.00

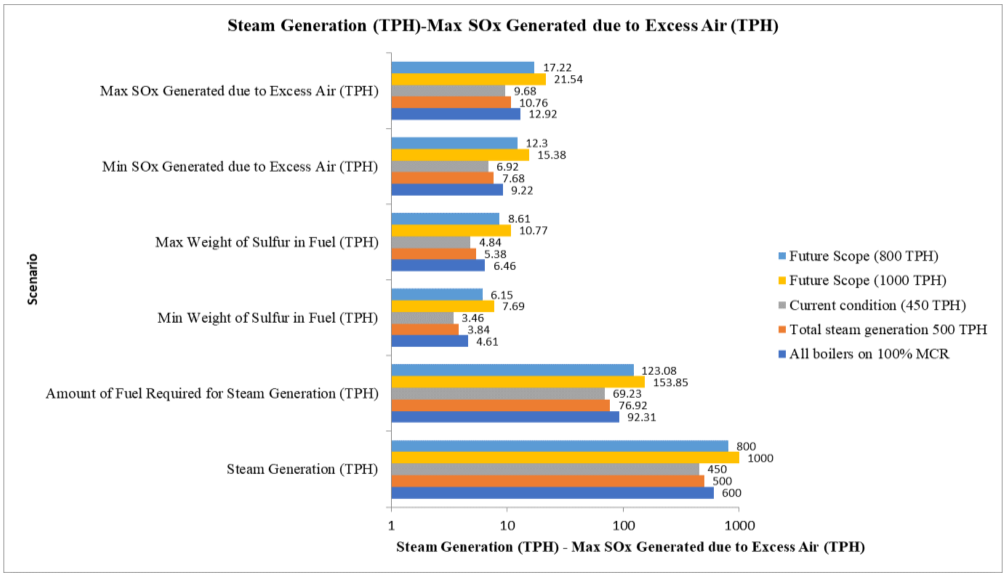

Fig. 1 Comparison of steam generation parameters and environmental impact

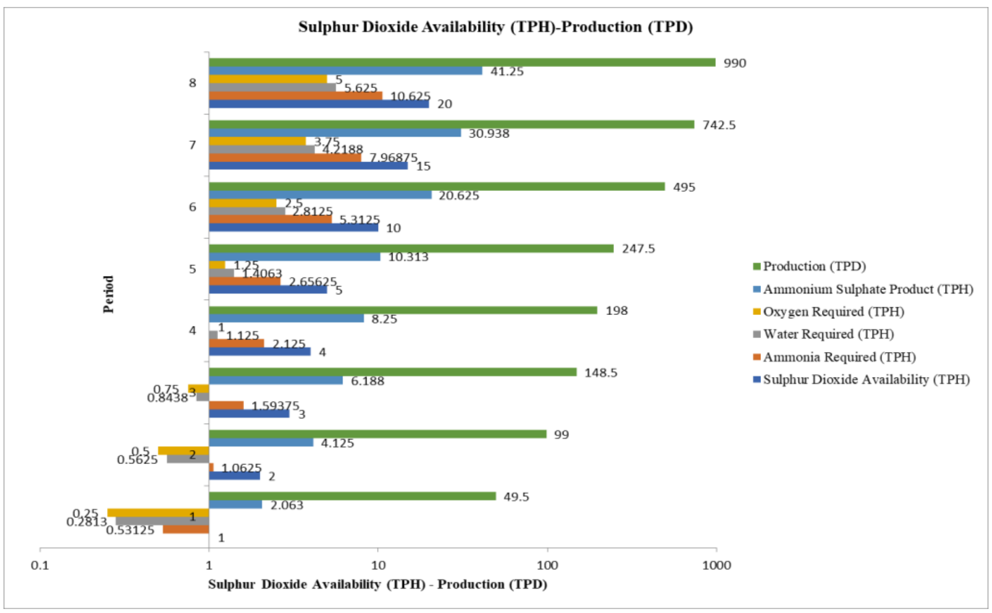

Fig. 2 Production scale-up of ammonium sulphate via chemical reaction parameters

Table 3. Potential revenue generation from waste flue gases: MET and JET Scenarios

Sulfur Dioxide Availability (TPH)	As per MET Scenario	As per JET Scenario
	Revenue Generation Scope (INR / year)	Revenue Generation Scope (INR / year)
1	274492683.8	86334728
2	548985367.5	172669455
3	823478051.3	259004183
4	1097970735	345338910
5	1372463419	431673638
10	2744926838	863347275
15	4117390256	1295020913
20	5489853675	1726694550

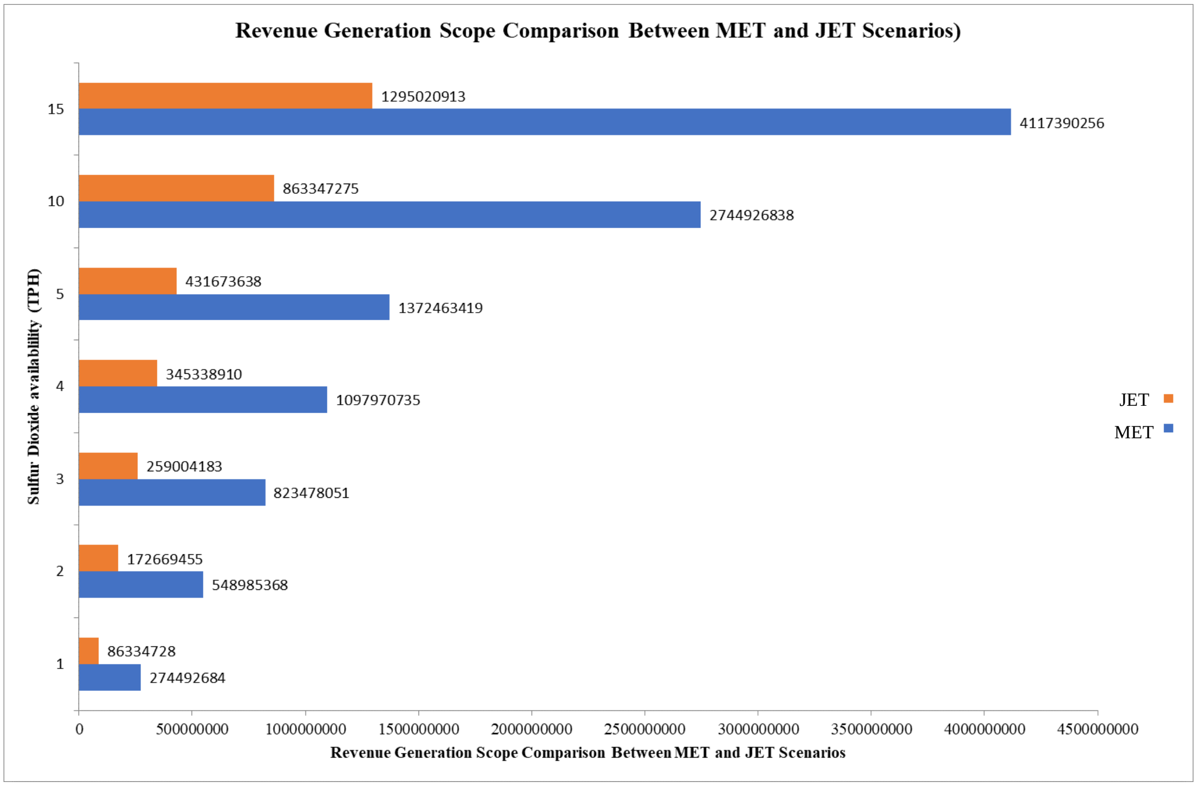

Fig. 3 Revenue generation scope comparison between MET AND JET scenarios

Fig. 4 Boiler system configuration at chemical complex

5. Conclusion

The feasibility analysis in this research paper indicates promising results for producing ammonium sulfate fertilizer from waste flue gas. Future endeavors should focus on optimizing the conversion process for increased efficiency and yield through experiments, fine-tuning parameters, exploring catalysts, and adopting novel technologies. Scalability is a key consideration, requiring efforts to transition from laboratory to pilot or industrial scale. This entails designing larger-scale production facilities, conducting commercialization feasibility studies, and addressing technical and economic challenges during scale-up.

An essential element for forthcoming research entails undertaking a thorough Life Cycle Assessment (LCA) to assess the environmental implications and sustainability of ammonium sulfate production. This assessment will quantify environmental advantages, including decreased greenhouse gas emissions and reduced waste generation, thereby offering valuable insights for decision-makers.

Table 1 provides valuable insights into the relationship between petcoke as a fuel, sulfur content, steam generation, and Sox generation in the chemical complex's boilers. Lower steam generation results in reduced fuel consumption and, consequently, lower Sox emissions. Future scenarios with increased steam generation capacities show a proportional increase in fuel consumption and Sox emissions.

The chemical balance equation emphasizes the importance of Oxygen in the formation of sulfur dioxide, underscoring the need for efficient combustion and air control to minimize environmental impact. Overall, the data presented in the table is crucial for assessing the environmental impact of boiler operations and can guide decisions regarding fuel usage and emission control in the chemical complex.

In Table 2, the Ammonia-based WFGD system presents a scalable solution for SO_2 removal in the Nirma context. The increasing demands for ammonia, water, and Oxygen, coupled with growing ammonium sulfate production, underscore the system's adaptability to varying SO_2 removal capacities. This information is vital for environmental compliance and sustainable industrial practices.

The byproduct, ammonium sulfate, not only contributes to environmental stewardship but also holds economic potential. The results and discussions from this table provide a foundation for strategic planning and decision-making in the implementation of Ammonia-based WFGD systems for SO_2 emission control. In conclusion, the feasibility analysis establishes a solid foundation for developing a sustainable process for producing high-quality fertilizer from waste flue gas.

In conclusion, the analysis highlights the substantial economic potential of utilizing waste flue gases for revenue generation in both MET and JET scenarios. The MET scenario demonstrates exponential growth in revenue generation with increasing sulfur dioxide availability, indicating significant opportunities for maximizing revenue. Conversely, the JET scenario presents a more modest linear growth trajectory but still offers economic viability. These findings underscore the importance of optimizing sulfur dioxide utilization strategies to capitalize on the economic benefits while ensuring environmental sustainability.

Further research and strategic planning are recommended to explore ways to enhance revenue generation while mitigating potential risks and ensuring regulatory compliance. Overall, the results suggest that leveraging waste flue gases for revenue generation holds promise for enhancing the economic sustainability of industrial operations.

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