REGRESSION ANALYSIS OF FACTORS AFFECTING ZINC RECOVERY IN ROTARY KILNS

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Abstract: With the rapid increase in global industrialization, the demand for zinc constantly increases while primary zinc resources gradually decrease. This situation makes the recovery of zinc from secondary sources a strategic priority from a circular economic perspective. Electric arc furnace (EAF) dust, an essential iron and steel industry waste, is a valuable secondary resource due to its high zinc content. Therefore, zinc recovery is an attractive option, given its low production cost. This study conducted an experimental analysis of the zinc recovery process from EAF dust in rotary kilns. Operational data obtained from an industrial-scale plant were used. The data set included EAF dust amount, iron content in EAF dust, lime content, coal used, slag amount, and zinc grade in slag. Multiple Linear Regression (MLR) analysis was applied to determine the relationships between the parameters. The MLR analysis calculated the multiple correlation coefficient (R) as 0.661876, and statistically significant relationships were determined between process parameters and slag formation. The findings provide a systematic and innovative approach for optimizing process parameters and controlling slag formation in industrial-scale zinc recovery processes. The analysis results indicated that raw material quantities and iron content in EAF dust significantly affect slag formation, contributing to zinc recovery efficiency and waste minimization. The developed model allows the systematic understanding and control of the effects of process parameters on slag formation while also providing a solid basis for future optimization studies.

Keywords: regression analysis, multiple linear regression, zinc recovery, EAF dust, rotary kiln

1. INTRODUCTION

The extraction of metals worldwide produces a range of goods and services that underpin modern society. This practice has been critical to human survival since the Bronze Age. However, over time, the production of metals has become fundamental to human development in an ever-widening range of fields. The 17th-century discovery of the secrets of refining pure zinc in Asia ushered in a growth in zinc mining and production in Europe from the mid-18th century. This was followed by a rapid increase in zinc production in the United States. Later in the 20th

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century, zinc found newer uses. These developments have enabled metals to evolve from basic building materials to versatile resources influencing modern industry and technology. The historical production of zinc by country and region is shown in Figure 1 [1].

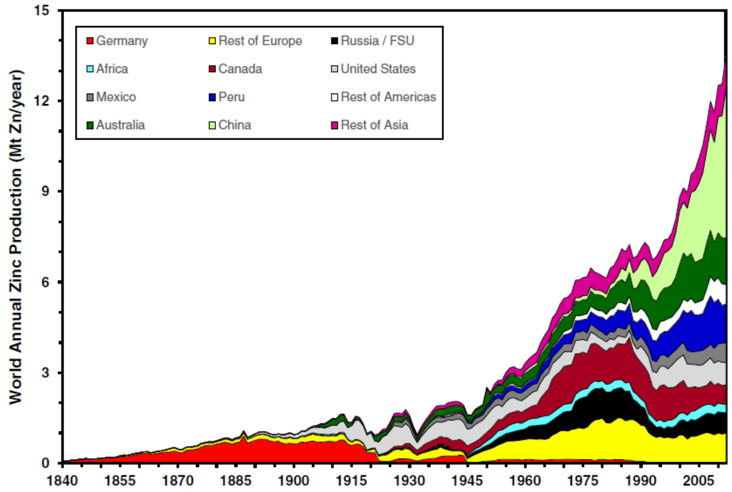

Fig. 1. Historical Zn production by country or region [1].

Zinc is a silvery bluish-gray metal with relatively low melting and boiling points of 420°C and 907°C, respectively. Zinc is brittle at average temperatures but can be formed at 100°C and easily rolled. Typically found in brittle form, it becomes a malleable metal when heated. Globally, zinc is the fourth most used metal and the third most used non-ferrous metal used after aluminum, and copper. The most common zinc mineral is sphalerite, also known as zinc blende. This mineral crystallizes from the hydrothermal solution as pure zinc sulfide (zinc sulfide) and is found in almost all currently mined zinc deposits. Zinc is often mined with lead, copper, silver, and other metals [2]. Zinc has pronounced corrosion resistance properties, making it an essential element in steel coating (galvanizing) to prevent rust. It can also combine with other metals to form alloys. Zinc can be combined with aluminum to produce the alloy used in die casting. Die casting forces molten metal into a mold cavity by applying high pressure [3]. Zinc demand in global markets includes the use of galvanizing steel and iron (50%), alloys (17%), brass and bronze (17%), semi-manufacturing (6%), chemicals (6%) and other applications in various sectors (4%) [2]. The demand for zinc and its production has increased by 4.7% and 2.7% per year, respectively, since 2012. At the current use rate, the demand for zinc will reach 2.7 times the current demand by 2050 [3]. Figure 2 shows the future sources of zinc production.

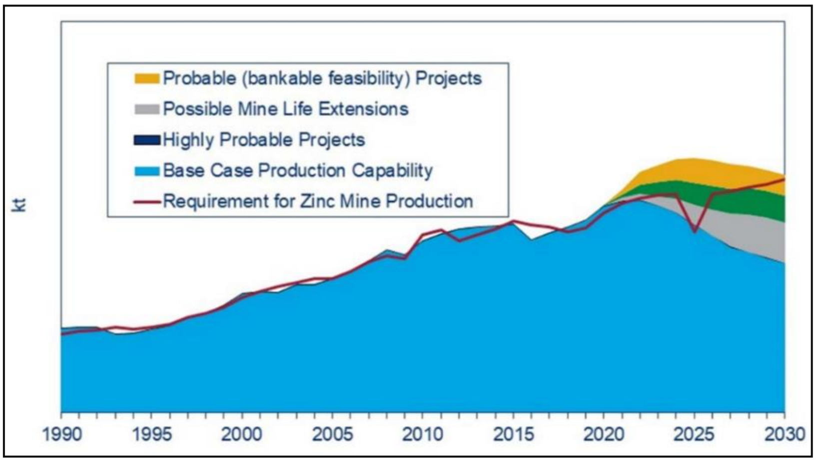

Fig. 2. Future sources of zinc mine production [4].

From 2016 to 2017, global zinc consumption increased by just over 2%. However, there are significant regional variations. India had the highest growth rate, increasing by almost 4% during this period. This rate is about 3% in China, while Europe, the US, and South Korea are 1.7 to 2.5% [5]. 2020 global refined zinc production increased to 13.8 million tons [6]. The production of 1 kg of zinc through primary mining from copper-lead-zinc-silver-gold ore containing 62% zinc consumes 23 MJ of fossil resources. It causes a global warming potential (100 years) of 0,8 kg CO2 equivalent. This equals 10.64 million tons of CO_2 annually, or 0.03% of global CO_2 emissions [3]. Electricity consumption during mining and smelting is the primary driver of greenhouse gas (GHG) emissions [6]. As shown in Figure 3, total zinc use increased to 19.5 million tons in 2019, with 6 million tons of zinc alloys (brass, sheet, and die-cast) and industrial waste being recycled without the need for refining (remelting). This shows that a single source of material is available to meet the overall annual demand for zinc. These recycling and recovery processes are an essential step towards sustainability. By meeting a large portion of zinc demand, recycling practices can reduce the need for raw zinc mining and contribute to more efficient use of natural resources [7].

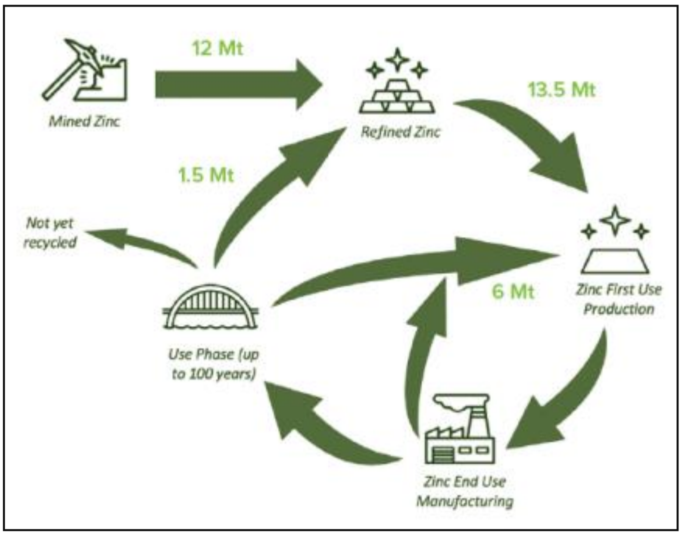

Fig. 3. Zinc utilization in 2019.

To reduce CO_2 emissions by 80% from current levels by 2050 (i.e., to reduce emissions below 2.13 million tons of CO_2 equivalent), the increased demand by 2050 needs to be met by recovering zinc from waste, i.e., from secondary sources. Recovering zinc from secondary sources is essential in the current circular economy. Zinc production and consumption are increasing globally, and primary sources of zinc from ore are rapidly depleting. Therefore, effective extraction of zinc from secondary sources can bring several advantages. These advantages include savings in raw resources and fossil resources used to power primary mining processes, increasing resource efficiency, reducing resource loss to landfills and dumps, avoiding loss of zinc or any metal to landfill, waste treatment, mitigation of environmental and health impacts, and improving economic performance of existing infrastructure. Secondary sources of zinc from waste include zinc in spent batteries, zinc in E-waste, zinc in wastewater, zinc in construction and demolition waste, zinc from steelmaking dust, zinc from municipal waste [3]. The electric arc furnace method (EAF) is used for recycling scrap. However, recycling these wastes and iron by-products using EAF is associated with the emission of dust particles, which, according to the United States Environmental Agency (EPA), are considered hazardous solid waste [8]. Due to its chemical and physical properties, EAF dust is classified as hazardous waste according to the European Waste Catalogue, where hazardous substances are present above a threshold concentration [9]. EAF dust is produced from the evaporation of heavy metals and silica particles during the melting of steel scrap [8]. During the melting of scrap, volatile components are removed by fumes and collected with particulate matter in the waste gas cleaning system. During the metal melting process, EAF can reach temperatures of 1600°C or higher. Many charge components, including iron, zinc, and lead, evaporate and enter the vapor phase. Dust is generated when the vapor is cooled and collected [9]. This dust is produced at a rate of 10-20 kg per ton of steel, which could mean that as much as 5-7 million tons of high dust is produced yearly. However, this powder contains a fair amount of heavy metals such as zinc, which contains 20-30 wt% zinc oxide. Given the low production cost, recovering zinc at such a high percentage is an attractive option. Two main technological processes extract zinc from EAF dust: pyrometallurgical and hydrometallurgical methods. The pyrometallurgical method is costly due to the enormous energy consumption and the need for reductants to produce zinc oxides with low commercial value. It also results in the emission of toxic gases, which are considered an environmental problem. The hydrometallurgical method is more advantageous than the pyrometallurgical method regarding process economy and environment [8].

Pyrometallurgical zinc production is carried out using five different methods, including zinc production from ore, recovery processes, the retort process, the shaft furnace process, the walls process, the Laclede process, and the Zero Thermal Throttling (ZTT) ferrolime process. The retort process involves not only the reduction of zinc oxide but also the liquefaction of zinc vapor. Zinc oxide produced through the roasting process is subsequently reduced with carbon. With the retort process, zinc production includes not only the reduction of the oxide but also the liquidization of zinc vapor. Zinc oxide produced by the roasting process is reduced with carbon. This endothermic reaction starts at approximately 1100ºC and is completed at 1300ºC. As a result, zinc is obtained in the vapor phase. The shaft furnace process is a method used to extract metal from ore and is incredibly widely used in zinc production. Shaft furnaces use the oxidation of C to CO_2 and CO to achieve high temperatures. In this step, ore is added to the upper part of the furnace and is reduced under high temperature while slowly sliding down. During the reaction, a large amount of nitrogen is formed by the combustion of coke and reacts with the oxygen in the metal ore. This reduces the partial pressure of the metal. The gases formed because of the reduction pass into the condenser. At this stage, zinc and other metals are condensed and collected in liquid form. The zinc leaving the condenser is cooled to a suitable temperature. Separating other metals, such as lead, is more accessible at this temperature. Various methods are used to separate zinc and other metals, such as floating on the surface or taking advantage of the different densities of the metals. Finally, pure zinc is collected and prepared for processing. This is usually done by floating on a dam or a similar method [9]. The Waelz process is one of the most common zinc recovery processes today. The process begins when EAF dust, coke, anthracite, and lime are charged into the rotary kiln. At high temperatures, the zinc in the EAF dust passes into the gas phase. The Waelz process is discussed in more detail in the Materials and Methods section. In the Laclade process, zinc and lead dust and reducers are charged into a closed electric furnace. The oxides undergo reduction reactions in the furnace, and the zinc and lead in the gas phase are obtained in metallic form. During this process, the zinc is recovered in a sprayed gas holder [10]. The ZTT ferrolime process involves pelletizing EAF dust and then reacting it with coke and coal in a rotary horizontal furnace to reduce its zinc. The smoke from the furnace contains zinc oxide, lead oxide, and cadmium oxide, and this smoke is captured to prevent further fuel carryover. These dusts are washed to enrich the zinc oxide, which is sold to producers [11].

Hydrometallurgical zinc production methods are carried out using five different methods: caustic soda leaching process, ammonium chloride leaching process, sulfuric acid leaching process, and iron nitrate leaching process. The caustic soda leaching process is accepted as a simple, cost-effective, and environmentally friendly process for zinc recovery from secondary sources containing zinc. Zinc and lead are dissolved separately in sodium hydroxide in the caustic soda leaching process. After zinc dust is purified, the leach solution is electrolyzed to produce sodium hydroxide. The ammonium chloride leaching process and processes such as Cenim-Lneti and Ezinex have also been developed to recover zinc from secondary sources using an ammonium chloride solution. The Cenim-Lneti process was developed for sulfur concentrates and other secondary raw materials. In this process, EAF dust is washed with water to dissolve ZnO and then leached with ammonium chloride. The Ezinex process was developed in Italy to process 500 tons of EAF dust annually to produce cathode zinc. In this process, ammonium-sodium chloride solution dissolves zinc within 1 hour and at 70-80°C. Metals such as copper, cadmium, nickel, and lead in EAF dust react similarly. However, iron oxides, ferrite, and silica do not dissolve at this stage. After the leach solution is purified, metallic zinc is produced by electrolysis in an open cell. Sulfuric acid leaching process: Another process used for zinc recovery with EAF dust involves sulfuric acid [12].

Iron nitrate leaching process. The recovery of valuable metals such as zinc and lead in EAF dust is carried out. In the process, EAF dust is weighed and taken to mills for fine grinding, water is added, and the EAF dust is turned into sludge. This sludge from the mill is washed by adding water to the tanks. The washed sludge is passed through filter presses. A certain amount of water is added to the sludge from the filtration, and its density is adjusted. Iron III Nitrate is added to the leaching process and mixed. At the end of the reaction, the sludge is passed through the filter press again to separate the sludge and the liquid containing metal ions. After the reaction is over in the sedimentation tank, the solution is sent to the third filter. Solid zinc hydroxide and lead hydroxide from the filter are obtained as the final product [13]. The chemical composition of EAF powder depends mainly on the quality of the steel scrap processed and the type of steel produced. Table 1 shows the chemical composition of the principal oxides of EAF powder [9].

As previously demonstrated, zinc recovery has become an essential strategic priority in the circular economy context. With the rapid increase in global industrialization, the demand for zinc constantly increases while primary zinc resources gradually decrease. This situation makes zinc recovery from secondary sources a strategic priority from a circular economic perspective.

Table 1. Chemical composition of EAF powder [14].

Oxides	wt.%
SiO_2	1.145
Al_2O_3	0.519
Fe_2O_3	24.780
CaO	18.600
MgO	3.949
K_2O	1.804
Na_2O	2.440
SO_3	3.214
Cr_2O_3	0.194
PbO	6.016
ZnO	25.290
MnO	2.452
CoO	0.24
CuO	0.454
Cl	3.622
LOI	6.450

EAF dust from the iron and steel industry is a valuable secondary resource, mainly due to its high zinc content (15-35%). This study conducted an experimental analysis of zinc recovery processes from EAF dust in rotary kilns. Operational data obtained from an industrial-scale plant was used. The dataset includes the parameters of EAF dust amount, iron content in EAF dust, lime amount, coal (anthracite coke) amount used, slag amount formed, and zinc grade in slag. Multiple Linear Regression (MLR) analyses [15,16] performed on industrial data systematically examined the effects of process inputs on slag formation. As a result of the analysis, the multiple correlation coefficient (R) was calculated as 0.661876. This value shows that the developed model offers promising results in explaining the complex relationships between process parameters and has the potential to be further improved with further studies. The analysis results show that the raw material amounts and the iron content in the EAF dust statistically affect the slag amount. These findings provide an innovative approach to control slag formation and process optimization in industrial-scale zinc recovery plants. The focus of the study is to gain an in-depth understanding of zinc recovery processes from a scientific perspective through regression analysis.

The main contributions of this study are:

- MLR analysis determined the statistically significant effects of EAF dust amount, iron content in EAF dust, coal and lime amounts on slag formation.
- EAF dust amount proved to be the most influential parameter on slag formation.
- The developed regression model provides a structured approach for optimizing process parameters and slag control in zinc recovery processes.
- The study results have significant potential for increasing the efficiency of zinc recovery processes and minimizing waste.
- MLR analysis is a powerful statistical method for modeling and estimating the relationship between variables.

2. MATERIAL AND METHOD

In this study, the method used to obtain the data is the Waelz process for zinc recovery in rotary kilns. The rotary kiln, one of the leading equipment used in the Waelz process, has a length of 65 m, a diameter of 4.4 m, a slope of 2%, and a rotational speed of 1.1 rpm, as shown in Figure 4 in this study. The interior of the rotary kiln is lined with high alumina refractory bricks. The reason for this is to prevent irreversible damage to the furnace's inner and outer sheet metal because the furnace's internal temperatures can reach 1200 C and higher. The Waelz process starts with adding raw material to the rotary kiln. The data used in the study are the results of samples taken from raw materials and outputs. Before feeding raw materials, hourly samples were taken from all raw materials to know at what rate and in what content the furnace system should be charged. The raw materials are mainly EAF powder, anthracite coal, coke, pelletized EAF powder, and lime. These raw materials are charged to the pre-roasting zone of the furnace with the help of conveyors in specific sizes through a feeding pot.

The ZnO(g) that evaporates because of these reactions is drawn to the section called dust room using negative suction system fans. One of the rotary kiln outputs because of these reactions is zinc oxide, and one of the other outputs is slag with high iron content. The inability to recover zinc healthily may also be due to the low zinc content in the raw material charged to the furnace, insufficient temperature for chemical reactions in the furnace, insufficient air supply, ring formations in the furnace, insufficient oxidation of the material coming to the slag exit zone. The ideal zinc content in the raw material is 27-28%; in the slag, this ratio is a maximum of 1%. In this study, MLR analyses of raw material inputs and rotary kiln outputs were carried out. Some values of the raw materials charged to the rotary kiln and the slag output are shown in Table 2.

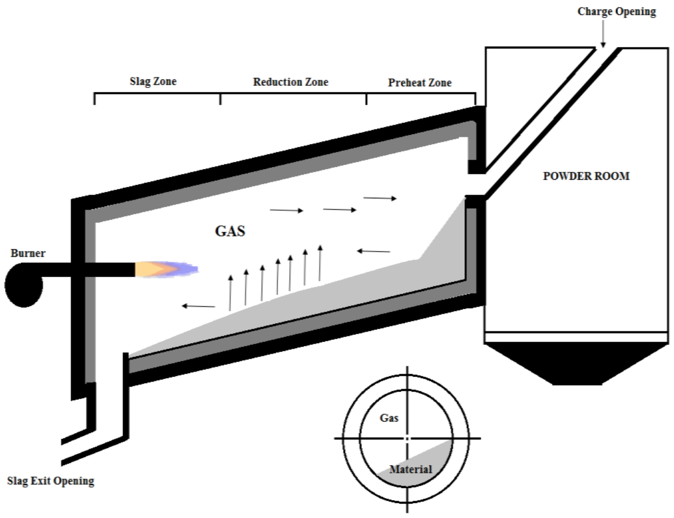

Fig. 4. Waelz process rotary kiln zones.

Table 2 includes the mean, maximum, minimum values, and standard deviations of the relevant process inputs (EAF dust, lime, and coal) in zinc recovery processes using EAF dust. In addition, the amount of slag formed and the zinc grade in the slag are also reported. The mean value for EAF dust was determined to be 398.26 tons, while the highest value was 458 tons, and the lowest was 71 tons. The standard deviations show the variability in the dataset and thus provide information for process optimization. MLR [17] was applied to these data, and the effects of process inputs on slag formation were systematically investigated.

In the Waelz process, the slag zinc tenor is a critical parameter in assessing the efficiency of the process and the zinc recovery rate. In an ideal Waelz process, the zinc remaining in the slag (grade) should be low. This means most of the zinc is recovered by evaporation and collected as zinc oxide. However, typically, a 1-10% zinc grade can still be found in the Waelz slag.

Table 2. Statistical analysis of EAF powder and process inputs used in MLR, including average, maximum, minimum, and standard deviation [13].

	EAF powder (tone)	Lime (tone)	Coal (anthracite+coke) (tone)	Slag (tone)	Slag Zinc Tenor
Average	398.26	37.73	142.87	252.33	0.92
Maximum	458	66	203	460.55	5.34
Minimum	71	4	102	31.65	0.21
Std. Deviation	40.59	10.74	10.41	60.34	0.69

3. RESULTS AND DISCUSSION

Regression analysis in zinc recovery provides a comprehensive analysis to evaluate the efficiency of the process, understand the relationships between factors, and optimize the process. The analysis is used to reveal complex relationships between various factors. These factors can be variables that are influential in the process. By identifying the links between these factors, the analysis enables strategies to be created to improve the overall efficiency of the process. Regression analysis also provides a statistical approach to ensure the statistical reliability of the zinc recovery process. This increases the reliability of decisions based on the analysis results and contributes to more precise process management. Determining the correct ratios and interactions between components can significantly impact production efficiency, energy consumption, and final product quality.

In this context, regression analysis identifies the optimal interactions between the components by determining the effects of the amount of EAF powder, lime, and anthracite coke blend on the furnace output. This enables the recovery process to be managed more efficiently. The analysis reveals potential for improvement in the process, providing the opportunity to reduce waste, increase recycling, and ensure a more efficient production process regarding environmental sustainability.

The multiple r used in regression analysis indicates the relationship between the dependent and independent variable and takes a value between 0 and 1. As this value approaches 1, it is understood that the relationship between dependent and independent values is vital. R-squared gives the ratio of the dependent variable, in short, the actual desired result, explained by the independent variables. As this value approaches 1, it is concluded that the independent variables explain a large proportion of the dependent variable. Adjusted r-squared prevents the regression model from increasing with the addition of more independent variables and makes corrections when it encounters r-squared [15]. It takes a value between 0 and 1, and as this value approaches 1, the explanatory power of the relationship between the dependent variable and the independent variable increases. Standard error indicates the amount of error expected from the regression. ANOVA (Analysis of Variance) is known as the analysis of variance. This analysis is used to compare means between all groups. While the F value expresses the ratio of variability between groups and variability within groups, the significance F-value tells whether the difference between groups is significant. If this value is 0.05 or less, the difference between the groups is considered statistically significant. While the coefficients express the effect of the variables in the regression, the p-value indicates whether the coefficients are significant or not [16].

A simple linear regression model with Y as the response variable, X_1 as the explanatory variable, β_0 and β_1 as the unknown parameters, and ε_i as the error term accounting for variation. The MLR model for p explanatory variables and n observations is given in Eq. 1 for p explanatory variables and n observations [15, 16].

$$Y_i = \beta + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_p X_{pi} + \varepsilon_i \quad (1)$$

The regression model can be described as follows:

- Y_i i-th observation value of the dependent variable,
- $X_{1i}, X_{2i}, \ldots\ldots, X_{pi}$ values of the first, second, ..., p-th explanatory variables for the i-th observation, respectively,
- $\beta_o, \beta_1, \beta_2, \ldots\ldots, \beta_p$ coefficients,
- ε_i error term (difference between the observed value and the value predicted by the model),

The regression equation is given by:

Regression equation = Intersection Coefficient + EAF Powder Coefficient · EAF Powder Value + Lime Coefficient Lime Value + Coal Coefficient · Coal Value + Iron Content Coefficient · Iron Content Value+ ε_i

Table 3 provides a comprehensive summary of the MLR analysis results, highlighting key statistical measures. When Table 3 is examined, the Multiple R-values obtained in the study was calculated as 0.661876. This shows that the relationship between the independent and dependent variables is at a medium level. The R Square value is 0.43808, which reveals that the independent variables explain approximately 43.8% of the variance of the dependent variable. The Adjusted R Square value was calculated as 0.43141, which reduces the explanatory power by considering the number of variables to provide a better fit for the model. The Standard Error value obtained, 46.65061, shows the average deviation of the estimates, affecting the model's accuracy. These results indicate a significant potential for the model to explain the effect of the independent variables on the dependent variable.

Table 3. Summary of the MLR analysis, including key statistical metrics.

Regression Statistics	
Multiple R	0.661876
R Square	0.43808
Adjustable R Square	0.43141
Standard Error	46.65061

When the ANOVA results for the MLR analysis in Table 4 are examined, the F value calculated for the regression is 65.6822559. This high F value shows that the model significantly explains the effect of the independent variables on the dependent variable. In addition, the significant F-value (p-value) has a meager value of 4.94546E-41. This reveals that the model is generally statistically significant and that the probability of the effects of the independent variables on the dependent variable being coincidental is extremely low. Therefore, these findings support the reliability and validity of the regression model and show that the results obtained are significant.

Table 4. Analysis of variance (ANOVA) for MLR.

-	F	Meaningfulness F
Regression	65.6822559	4.94546E-41

Table 5 shows the results of MLR analysis, which reveals the effects of independent variables such as EAF dust, lime, coal, and iron content on the dependent variable. The intercept value is -136.1628584, and the p-value is 0.00013, which significantly shows the expected value of the dependent variable when the independent variables are zero. It is observed that EAF dust has a highly significant positive effect with a coefficient of 0.560250621 and a p-value of 7.1E-23. In contrast, coal has a significant positive relationship with a coefficient of 0.464561692 and a p-value of 0.00823. However, the coefficient calculated for lime is 0.355345395, and the p-value is 0.22424, which shows that this variable does not have a statistically significant effect on the dependent variable. The amount of lime with a p-value greater than 0.05 can have a negligible effect on the amount of slag compared to other variables. Iron content has a robust positive effect with a coefficient of 4.958411486 and a p-value of 0.00799. As a result, the effects of EAF dust, coal, and iron content on the dependent variable are significant, but it is understood that the amount of lime should not be considered in this model. As a result of the MLR analysis, it was observed that the amounts of raw materials and the iron ratio in the raw material significantly affected the amount of slag, considering the size and character of the dataset.

Table 5. Coefficients and P-values from the MLR intercept analysis.

Intercept analysis	Coefficients	P-value
Intersection	-136.1628584	0.00013
Eaf powder	0.560250621	7.1E-23
Lime	0.355345395	0.22424
Coal	0.464561692	0.00823
Iron content	4.958411486	0.00799

Based on the MLR analysis, the mathematical relationship between the variables can be expressed as:

Y = -136.1628584 + 0.560250621(EAF powder) + 0.355345395(Lime) + 0.464561692 (Coal) + 4.958411486 (Iron content)

The model shows statistical significance overall, with an F-significance value of 4.94546E-41 ($p < 0.05$), confirming that the regression model is a good fit for the data. The correlation coefficient (Multiple R = 0.6619) suggests a moderately strong relationship between the predictor variables and the dependent variable. The coefficient of determination ($R^2 = 0.43808$) indicates that approximately 43.81% of the variance in iron content is explained by the model, highlighting a meaningful but not extremely strong explanatory power. Analysis of the individual predictors shows that EAF powder (p = 7.1E-23) and Coal (p = 0.00823) are statistically significant predictors at a significance level of α = 0.05. However, Lime (p = 0.22424) does not reach statistical significance, implying that it may not have a meaningful impact on iron content in this context. The intercept coefficient (-136.1629) is also statistically significant (p = 0.00013), representing the theoretical iron content when all independent variables are set to zero.

4. CONCLUSIONS

The rapid increase in global industrialization and the gradual decrease of primary zinc resources make zinc recovery a strategic priority. This study has demonstrated the importance of regression analysis in optimizing the zinc recovery process from EAF dust. The regression analysis results determined statistically significant relationships between process parameters and slag formation with a multiple correlation coefficient of 0.661876. The analysis showed that raw material amounts and iron content in EAF dust significantly affect slag formation. These findings provide a systematic approach to increasing zinc recovery efficiency and waste minimization. The developed model allows systematic understanding and control of the effects of process parameters on slag formation. This analytical approach provides a solid basis for future optimization studies in industrial-scale zinc recovery processes.

Regression analysis is a powerful methodological tool for increasing efficiency and improving waste management in complex industrial processes. According to the analysis results of the study, regression analysis provides a comprehensive analysis to evaluate the efficiency of the zinc recovery process, understand the relationships between factors, and optimize the process. The analysis is used to reveal the complex relationships between various factors. By identifying the links between these factors, regression analysis enables strategies to be developed to improve the overall efficiency of the process. Furthermore, regression analysis provides a statistical approach to ensure the statistical reliability of the zinc recovery process.

The findings of the study reveal important results in terms of determining the factors affecting the amount of slag based on MLR analysis and these results are summarized below:

- According to the results of MLR analysis, it was observed that the number of raw materials and iron content in raw materials significantly affected the amount of slag.
- The slag amount depends on the change in raw material and iron ratio. This means that while the slag amount increases or decreases due to the change in raw material amount and iron ratio.
- All the values in the table are significant because the significance level F value is less than 0.05. This indicates that the null hypothesis is rejected; therefore, there is a statistically significant difference between the groups.
- Since the p-value of lime content is more significant than 0.05, it can be concluded that lime content has less effect on slag content than other factors.
- According to the p-value, the most significant items on the slag amount are EAF powder, iron ratio, coal, and lime, respectively.
- The amount of slag increases with the increase in raw material and iron ratio. If the zinc content in the slag amount is more than 1%, zinc loss occurs in the slag, and in this case, it can be said that the Waelz process cannot be done correctly, and zinc cannot be recovered.
- If the amount of slag increases but the zinc content remains below 1%, it can be said that the Waelz process is being carried out properly because the zinc content in the slag is low. Zinc is not lost in the slag, and optimum conditions are obtained in the rotary kiln.
- The amount of slag and the zinc content in the slag are inversely proportional. To improve the process, the amount of slag should be increased, and the zinc content in the slag should be decreased. The conditions required for this situation can be briefly stated as sufficient temperature, sufficient air, prevention of ring formations, and sufficient oxidation in the slag exit zone.
- There is no connection between the number of raw materials and the increased iron and zinc content in the slag.

This increases the reliability of the decisions made based on the analysis results and contributes to a more precise management of the process. According to the MLR analysis results, the amount of EAF dust, the amount of lime, and the amount of anthracite-coke coal mixture have determinant effects on the furnace output. This analysis provides an opportunity to provide a more efficient production process in terms of increasing recycling by revealing the potential for improvement in the process. In conclusion, this research clearly demonstrates the potential of regression analysis in optimizing the zinc recovery process from EAF dusts and provides valuable insights for future industrial applications.

Future research will focus on expanding the dataset, integrating high-precision sensor technologies, and applying advanced machine-learning algorithms to optimize the zinc recovery process. The proposed work aims to increase process efficiency by developing hybrid predictive models. Furthermore, applying Internet of Things (IoT)-based systems and advanced statistical modeling techniques will provide more comprehensive insights into slag formation dynamics and process efficiency. Furthermore, the development of multi-criteria decision support systems and environmental impact analyses will contribute to a more holistic understanding of zinc recovery from electric arc furnace dust within the framework of a circular economy.

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