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(Research Article)

Fuzzy logic optimization of moisture content in boiler wood fuel used in tea factories in Kenya

Kamunge Moses Muriuki *, Peter Okemwa and Isaac Wanjala Nangendo

Department of Technology Education, School of education, University of Eldoret –Kenya.

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Abstract

This research investigates the use of fuzzy logic to optimize the moisture content of wood fuel used for boilers in Kenya's tea processing factories. Moisture levels are crucial as they influence combustion efficiency, energy production, and emissions levels. Integration of a fuzzy logic control system into the wood-fired boiler significantly reduced the moisture content from an initial 23% to a more optimal 18%, as determined by simulation outcomes. This 5% reduction in moisture content was accomplished through the dynamic adjustment of various boiler operating parameters, in this case, fuel feed rate, combustion airflow, and steam pressure, integrating a fuzzy logic algorithm that drew insights from both expert and real-time sensory data. The simulated operation of the fuzzy logic control system showed an enhancement in boiler efficiency of up to 81%, a decrease in emissions of up to 178g/kWh, and an overall improvement in system reliability, thereby demonstrating the efficacy of integrating fuzzy logic in wood-fired boiler for enhancing performance and addressing moisture-related challenges.

Keywords: Fuzzy Logic; Moisture Content; Wood Fuel; Boilers; Efficiency

1. Introduction

The tea processing industry is a vital component of Kenya's economy, contributing significantly to export revenues and employment opportunities. Boilers powered by wood fuel are commonly used for energy generation in tea processing but, are often plagued by inefficiencies stemming from variability moisture content in the fuel (Ogot et al., 2020). Excessive moisture in wood fuel can lead to lower combustion efficiency, increased emissions, and reduced energy output. This paper investigates the use of fuzzy logic systems in wood fuel, for moisture content optimization to enhance boiler performance in the Kenyan tea processing sector.

2. Literature review

2.1. Tea Processing in Kenya

Tea processing is a crucial step in the tea production chain that significantly impacts the quality, marketability, and profitability of tea in Kenya. As one of the leading tea producers globally, Kenya's economy relies heavily on this sector. The processing of tea involves several stages, including withering, rolling, fermentation, drying, and sorting, which determine the final product's characteristics and quality.

The tea sector is a vital contributor to Kenya's economy subsequently providing employment and supporting livelihoods for millions of people. It is one of the country's leading foreign exchange-earners. Approximately 30% of all agricultural exports is made up of tea, and therefore, processing plays a key role in enhancing its value (Karachi & Suri, 2021).

* Corresponding author: Kamunge Moses Muriuki.

Processing techniques directly affect the flavor, aroma, and health benefits of tea. Properly processed tea yields higher quality products that can fetch premium prices in international markets. Innovations in processing technologies, such as mechanization and automated quality control systems, have enabled Kenyan tea processors to meet global standards (Ng'ang'a et al., 2022).

Tea processing not only improves quality but also facilitates value addition. As consumer preferences shift towards specialty teas, processing methods that enhance the distinctive qualities of Kenyan teas are increasingly important. This diversification and specialization are crucial for maintaining competitiveness in the global tea market (Kamau et al., 2023).

Sustainable processing practices are gaining attention as global consumers become more environmentally conscious. There is a growing emphasis on eco-friendly processing methods that minimize waste and reduce environmental footprints (Mutuku & Karanja, 2023). Implementing sustainable practices in tea processing helps conserve resources and enhances the appeal of Kenyan tea to environmentally conscious consumers.

2.2. The Significance of Fuel Quality in Boilers

Wood fuel is often the primary energy source for many tea factories. However, variability in the moisture content of this fuel can adversely affect boiler efficiency. Research by Gitari and Chege (2019) indicates that moisture levels exceeding 25% can lead to significant energy losses and increased operational costs.

2.3. Fuzzy Logic Applications in Energy Management

Fuzzy logic is a computational approach that mimics human reasoning, offering advantages in handling uncertainties inherent in complex industrial processes (Zadeh, 1994). Studies have shown that fuzzy logic systems can optimize various parameters in industrial boilers, including fuel moisture content (Aydin & Koç, 2020). This method provides a basis for creating adaptive control systems capable of maintaining optimal moisture levels leading to enhanced combustion performance.

2.4. Critical literature review on optimization Techniques

Several studies have reported on optimization techniques for biomass boilers. For instance, Ahmad et al. (2021) utilized a fuzzy logic controller to regulate fuel feed rates based on moisture content, achieving a marked improvement in thermal efficiency. Similarly, Zhao et al. (2022) demonstrated how fuzzy algorithms can optimize biomass combustion processes by controlling various parameters based on real-time data. Additionally, Lee et al. (2023) explored the integration of machine learning algorithms in predicting optimal combustion conditions, resulting in increased efficiency and reduced emissions. Moreover, Tran et al. (2023) focused on the role of artificial intelligence in optimizing fuel quality assessment for biomass boilers, highlighting improvements in operational performance. Finally, Kumar and Raghav (2023) evaluated the impact of feedstock variability on biomass boiler efficiency, suggesting adaptive control strategies to enhance performance under different fuel conditions.

3. Materials and methods

3.1. System Design

This study proposes the use of fuzzy logic control system that comprises several components aimed at regulating the moisture content in wood fuel before it enters the boiler. The system incooperates several input variables such as initial moisture content, desired combustion temperatures, and ambient temperature.

3.2. Fuzzy Controller Structure

The fuzzy logic controller (FLC) is designed based on the following steps:

- Identification of input Variables: These include wood moisture content, operating temperature, and load demand.
- Determination of output Variables: The output adjusts the fuel feed rate and drying time.
- Development of fuzzy Rule Base: Based on expert knowledge, rules such as "IF moisture is high THEN increase drying time" will be defined.
- Defuzzification process: The center of gravity method to be used to convert the fuzzy output into a precise control signal.

3.3. Data Collection

Data was collected from selected tea processing facilities in Kenya, focusing on real-time moisture readings and operational parameters over a specified period. The collected data informed the development of the fuzzy logic system's parameters.

3.4. Simulation Environment

The design and implementation of the fuzzy logic controller was simulated using MATLAB/Simulink, allowing for visual feedback and data analysis of fuel efficiency and emissions. To develop fuzzy rules for improving the moisture content of wood fuel in a boiler following inputs and outputs variables were considered.

3.4.1. Input variables

Table 1 Data from wood fired boiler.

Observation	Current moisture content (CMC) (%)	Desired moisture content (DMC) (%)	Temperature (t) (°c)	Load demand (LD) (%)
1	20	15	180	75
2	18	15	170	80
3	22	15	190	70
4	21	15	184	60
5	19	15	176	85
6	17	15	182	65
7	15	15	178	90
8	16	15	188	55
9	23	15	194	50
10	24	15	192	40

3.4.2. Fuzzy Rule Base

Based on expert knowledge and empirical data, the following fuzzy rule base was developed:

Table 2 Expert-based fuzzy rules

Rule id	Condition	Action	Fuzzy logic representation
1	CMC High	LD High	IF (CMC is High) AND (LD is High) THEN (DT is Short)
2	CMC Medium	T High	IF (CMC is Medium) AND (T is High) THEN (DR is Medium)
3	DMC Reached	CMC Close to DMC	IF (DMC is Reached) AND (CMC is Close to DMC) THEN (DT is Very Short)
4	CMC Low	LD Low	IF (CMC is Low) AND (LD is Low) THEN (DT is Medium)
5	CMC High	T Low	IF (CMC is High) AND (T is Low) THEN (DT is Longer)
6	DMC Not Reached	CMC Above DMC	IF (DMC is Not Reached) AND (CMC is Above DMC) THEN (DT is Longer)

In this study, each rule in a fuzzy logic was assigned a unique identifier, known as the Rule ID, to facilitate easy reference and management. The condition section specifies the precise circumstances that must be met for the rule to be activated, essentially defining the trigger points for the rule's execution. Upon meeting these conditions, the rule executes a predetermined action, which represents the desired outcome or response. The fuzzy logic representation of the rule is mathematically expressed using the IF-THEN syntax, providing a structured format for representing and analyzing the rule's behavior.

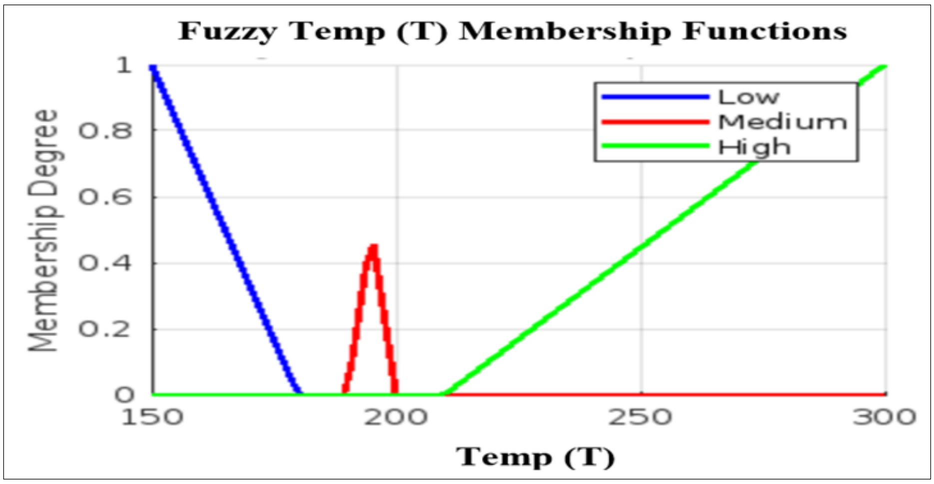
The rules outlined above are designed to achieve several objectives. Firstly, they aim to reduce drying time in situations where both the current moisture content and load demand are high. Secondly, the rules seek to increase the drying rate when the current moisture content is at a medium level and the temperature is high. Thirdly, they indicate that drying should be stopped once the desired moisture content is achieved and the current moisture content is nearing this target. Additionally, the rules are intended to maintain a moderate drying time when the current moisture content and load demand are both low. Conversely, they suggest prolonging the drying time when the current moisture content is high and the temperature is low. Finally, the rules also call for an increase in drying time if the desired moisture content has not been reached and the current moisture content exceeds this level.

3.4.3. Membership Functions

The membership functions define how the variables map to their respective fuzzy sets (High, Medium, Low, etc.).

Table 3.3 Membership function for variables

Variable	Membership Function	Range
CMC	Low	[0%, 10%]
	Medium	[10%, 18%]
	High	[18%, 25%]
T	Low	[150,180]
	Medium	[190,200]
	High	[210-300]
LD	Low	[20%, 50%]
	Medium	[50%, 80%]
	High	[80%, 100%]



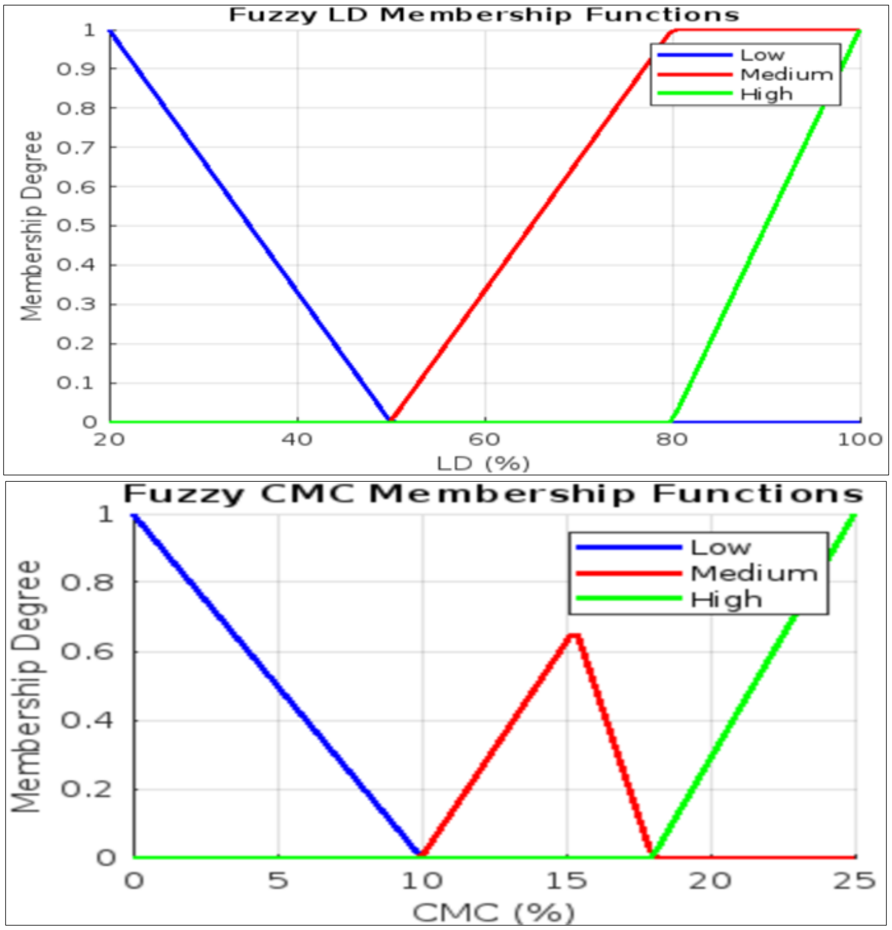


Figure 1 Membership functions for Temp (T), LD and CMC

The membership functions for the outputs (DR) map the input values to their respective fuzzy sets.

3.4.4. Defuzzification

Using the Center of Gravity method, the defuzzified outputs was calculated as follows:

The mathematical representation for the fuzzy outputs (Drying Rate DR) was expressed as follows:

Drying Rate=$k \cdot A \cdot (T - T_o) \cdot (M_o - M_t)$

Where:

- k = drying constant (specific to the material and conditions)
- A = surface area of the wood (m^2)
- T = temperature of the drying air (°C)
- T_o = initial temperature of the wood (°C)
- M_o = initial moisture content (kg)
- M_t= current moisture content (kg)

However, based on the available data k =0.729 kg/m, A=2m^2 , T=100^{o}c ,T_o =25 ^{o}C ,M=150 kg and M_o =50 kg .The calculated drying constant was determined to be 0.729 kg/m, leading to a predicted drying rate of 0.73kg/min under the specific conditions of the experiment. The result of the drying rate in this study was applied as a membership function in the developed fuzzy logic.

4. Results and Discussion

4.1. Simulation Results

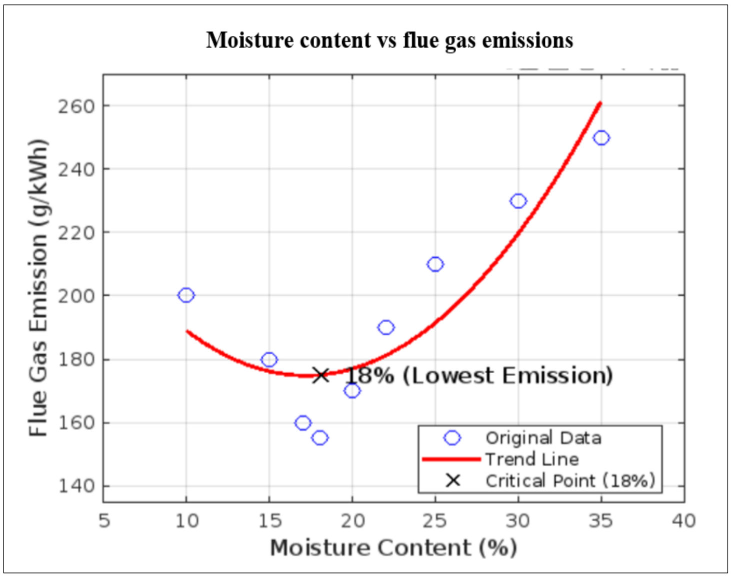


Figure 2 Graph for moisture vs flue gas

At 18% moisture content, the emissions level of 178 g/kWh indicates an acceptable combustion performance, balancing energy output and emissions release. This is typically an optimal moisture range for combustion; going above this might increase emissions due to incomplete combustion, while going much below could lead to dry fuel burning too quickly, potentially producing more nitrogen oxides (NOx) or other harmful emissions

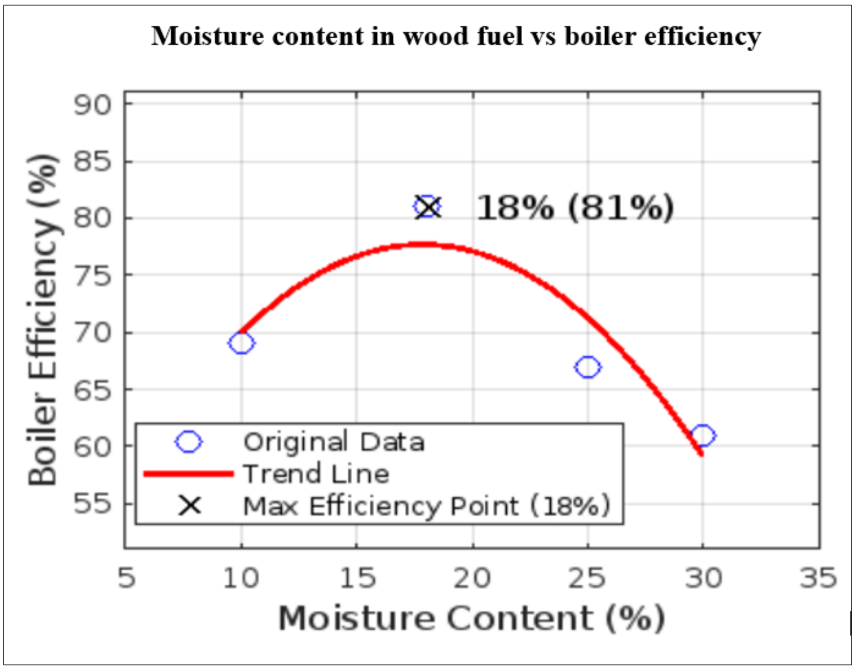


Figure 3 Graph for moisture vs boiler efficiency

The graph indicates that at a moisture content of **18%,** the boiler achieves its **peak efficiency of 81%.** This is an important operational characteristic, as it highlights the optimal moisture level for maximizing energy output from the boiler system.

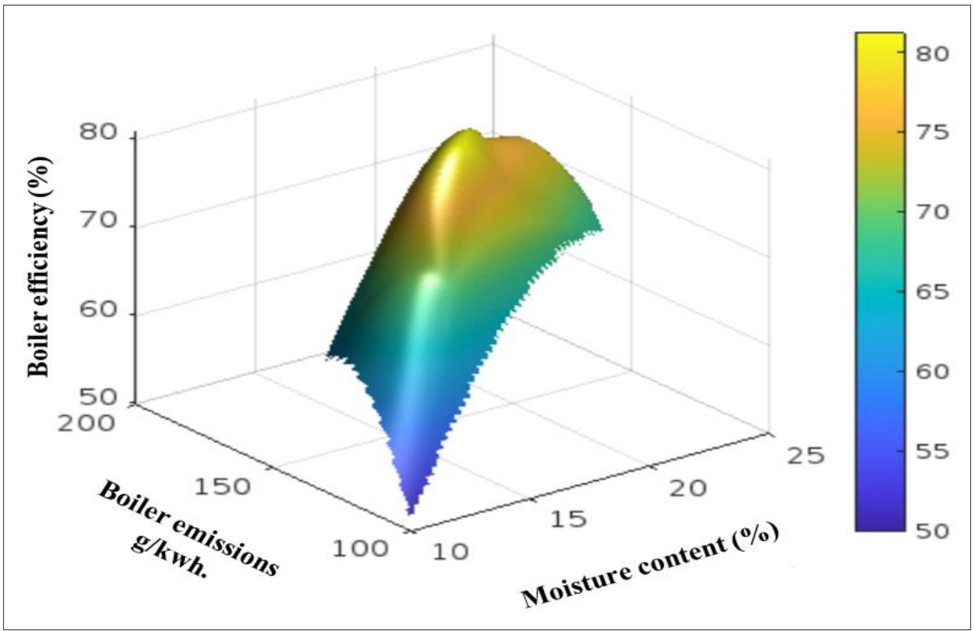


Figure 4 surface mesh for efficiency emission and moisture content

The graph indicates that at a moisture content of 18%, the boiler demonstrates a balanced performance with an emissions output of 178 g/kWh and an operational efficiency of 81%.

This moisture level is within the optimal range for combustion, which means the wood fuel is sufficiently dry to combust effectively while retaining enough moisture to avoid harmful combustion processes associated with overly dry fuel. The flue gas emissions value of 178 g/kWh signifies the number of pollutants released per unit of energy generated. This level of emissions can be viewed as acceptable or suitable, depending on regulatory standards and environmental benchmarks. It indicates a relatively efficient combustion process where the fuel is burned effectively, minimizing waste and energy loss. The 81% efficiency means that 81% of the input energy from the wood fuel is converted into useful energy output, while the remaining 19% is lost through processes such as heat loss in flue gases and unburnt fuel in ash. An efficiency level of 81% is generally considered good for wood-fired boilers, often falling within the range sought for optimized operation. This efficiency indicates that the system is well-tuned to minimize waste and maximize energy extraction from the fuel

4.2. Implications for the Tea Processing Industry

The findings underscore the importance of maintaining optimal moisture content in wood fuel. This optimization approach can lead to significant cost savings while improving the environmental footprint of tea processing operations.

5. Conclusion

The study demonstrates that the integration of fuzzy logic can effectively optimize moisture content in wood fuel used in boilers for the tea processing industry in Kenya. Future research should focus on integrating real-time data acquisition systems to enhance the adaptability of the fuzzy control system in operational settings.

Compliance with ethical standards

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Disclosure of conflict of interest

All authors of this manuscript agreed and contributed meaningfully to ensure that the paper comes out successfully without any conflict of interest.

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