СНИЖЕНИЕ ТЕПЛОПОТЕРЬ С ИСПОЛЬЗОВАНИЕМ ТЕПЛОВОГО НАСОСА-ОСУШИТЕЛЯ В СУШИЛЬНОЙ КАМЕРЕ НА СОЛНЕЧНОЙ ЭНЕРГИИ ДЛЯ ПОВЫШЕНИЯ ЭФФЕКТИВНОСТИ И СНИЖЕНИЯ РАСХОДА ДРЕВЕСНОГО ТОПЛИВА

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Аннотация: *В данном исследовании была разработана сушильная камера на солнечной энергии (SACB) с системой осушения для улучшения процесса сушки табака. Благодаря интеграции теплового насоса-осушителя для рекуперации отработанного тепла, модифицированная система значительно снизила эксплуатационные расходы и воздействие на окружающую среду. Результаты показывают снижение расхода древесного топлива на 54,28% и меньшее потребление электроэнергии по сравнению с традиционными методами. Осушаемая SACB оказалась более рентабельной, продемонстрировав более высокую окупаемость инвестиций. Это исследование подчеркивает потенциал интеграции систем осушения для повышения эффективности и устойчивости сельскохозяйственных практик, таких как сушка табака.*

Ключевые слова*: Сушильная камера на солнечной энергии, потребление древесного топлива, выбросы углерода, осушение*

REDUCING HEAT LOSS USING HEAT PUMP DEHUMIDIFICATION OF SO-LAR AIDED CURING BARN FOR INCREASED EFFICIENCY AND LOW FUELWOOD CONSUMPTION

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Abstract: *This study developed a Solar-Assisted Curing Barn (SACB) with a dehumidification system to improve tobacco curing. By integrating a heat pump dryer to recover waste heat, the modifiedsystem significantly reduced operational costs and environmental impact. Results show a 54.28% reduc-tion in fuelwood consumption and lower electrical use compared to traditional methods. The dehumidi-fied SACB proved more cost-effective, demonstrating a higher return on investment. This research high-lights the potential of integrating dehumidification systems to enhance the efficiency and sustainability of agricultural practices like tobacco curing.*

Keywords: *Solar Aided Curing Barn, Fuelwood Consumption, Carbon Emission, dehumidifica-tion.*

Introduction

The global pursuit of sustainable and efficient energy solutions is critical due to climate change and depleting fossil fuel reserves. Integrating renewable energy sources, such as solar power, is a pivotal strategy for reducing carbon footprints and fostering sustainable practices. Agriculture, a cornerstone of global food production, is also a significant contributor to greenhouse gas emissions, primarily from energy-intensive processes like crop drying. Traditional drying methods, often reliant on fuelwood, contribute to deforestation and incur substantial energy losses. This research proposes a novel approach: "Reducing Heat Loss Using Heat Pump Dehumidification of the Solar-Aided Curing Barn for Increased Efficiency and Low Fuelwood Consumption". By integrating heat pumps and solar energy, the aim is to revolutionize agricultural crop drying, enhancing efficiency, minimizing reliance on fuelwood, reducing carbon footprint, and offering economic benefits to farmers. This innovative approach envisions farmingpractices aligned with environmental conservation and economic viability.

Objectives

The general objective is to improve the efficiency and sustainability of agricultural crop drying by reducing heat loss through the integration of heat pump dehumidification in solar-aided curing barnsand minimizing fuelwood consumption.

Specifically, this study aimed to:

- Evaluate the performance of heat pump dehumidification technology in maintaining optimal dry-ing conditions within the SACB.
- Measure the reduction in fuelwood consumption compared to traditional drying methods.
- Identify and optimize key parameters (heat pump settings, solar energy configuration) for maxi-mum energy efficiency.
- Investigate the impact on reducing drying time while maintaining product quality.
- Quantify environmental benefits (reductions in greenhouse gas emissions and forest conserva- tion) and evaluate sustainability contributions.
- Analyze the economic feasibility by assessing initial setup costs and long-term operational sav- ings for farmers.

Materials and Methods

The research methodology systematically investigates the impact of integrating a dehumidifica- tion process into a solar-aided curing barn system to increase its efficiency in agricultural crop drying.

System Design and Setup

- **Solar Aided Curing Barn Design:** Site selection considered sunlight exposure, accessibility, and proximity to crop harvesting. Barn structure was designed based on crop type and ex- pected capacity, considering dimensions, orientation, roofing materials, and ventilation. Insu- lation materials were incorporated to minimize heat loss.
- **Heat Pump Dehumidification System Integration:** An appropriate heat pump system was selected based on barn size and requirements. Installation involved proper positioning and connection to the dehumidification unit. Ductwork was designed and installed for air circula- tion to maximize dehumidification efficiency and even drying. A control system with temper- ature and humidity sensors was set up.

Instrumentation and Data Collection: Data logging equipment was installed to record temperature, humidity, airflow rates, and energy consumption. Sensors were strategically placed inside and outside the barn. Instruments were set up to monitor crop moisture content before and after drying , and energy meters measured electricity consumption of the heat pump and auxiliary equipment.

Data Collection and Baseline Measurements: Baseline data included prevailing environmental conditions (ambient temperature, relative humidity, solar radiation) , initial barn parameters without dehumidification (internal temperature, humidity, airflow), initial crop moisture content , and energy consumption of existing barn equipment.

Data Analysis

- **Data Preparation:** Data was validated for accuracy and completeness, with outliers or errors addressed. Duplicates, inconsistencies, or irrelevant information were removed.
- **Descriptive Statistics:** Means, medians, standard deviations, and ranges for key variables (temperature, humidity, drying rates, energy consumption, crop moisture content) were generated. Graphical representations (histograms, box plots, scatter plots, time series plots) visualized trends and distributions.
- **Comparative Analysis:** Data from baseline and dehumidified runs were compared to quantify differences in temperature, humidity, energy consumption, drying rates, and crop moisture content. Statistical tests (t-tests, ANOVA) determined statistical significance of observeddifferences.
- **Correlation Analysis:** Pearson correlation coefficients explored relationships between variables (e.g., humidity and drying rates). Heat maps or correlation matrices visualized the strength and direction of relationships.
- **Regression Analysis:** Regression models were developed to explore deeper relationships (e.g., temperature and humidity on drying rates or energy consumption). Models were validated for goodness of fit and predictive accuracy.

Environmental Impact Assessment: Data on energy consumption (electricity and fuelwood) for both baseline and dehumidified runs was collected, including type and amount of fuelwood. Greenhouse gas emissions from fuelwood combustion (CO2) were gathered and estimated for both runs. Informationon local forest resources, deforestation rates, and the impact of fuelwood consumption was collected. Environmental impacts of baseline and dehumidified runs were compared and quantified in terms of energy savings, emissions reductions, and forest resource conservation. Sensitivity analyses assessed theinfluence of key variables and assumptions.

Results And Discussion

Performance of the Dehumidification System: Performance was assessed based on fuelwood consumption, electrical consumption, curing duration, drying and moisture content reduction rate, and fuel to cured leaf ratio. Correlation and regression analyses examined relationships between temperature, fuelwood, and electricity consumption in both ventilated and dehumidified systems.

Average Fuelwood and Electrical Consumption: Fuelwood consumption is influenced by to- bacco volume. Table 1 presents average values. The average tobacco volume for ventilated and dehu- midified systems was 1,351.98 kg and 1,000.19 kg, respectively. Average fuelwood consumption was 966.00 kg for ventilated and 461.42 kg for dehumidified systems. Electrical consumption averaged 82.80 kWh for ventilated and 64.20 kWh for dehumidified systems.

The dehumidified system reduced fuelwood consumption by up to 54.28%. For example, 966.00kg of fuelwood cured 1,351.98 kg of fresh tobacco (71.45% of volume) in the ventilated system, while 461.42 kg cured 1,000.19 kg (46.13% of volume) in the dehumidified system. The dehumidified system also showed lower electrical consumption, suggesting less electricity needed to maintain the curing chamber load.

Tabl 1

Average fuel and electrical consumption in tobacco flue-curing using ventilated and dehumidified sys-tem

Curing No.	Tobacco Vol-ume, kg (A)	Tobacco Vol-ume, kg (B)	Fuelwood, kg (A)	Fuelwood, kg (B)	Electrical, kWh (A)	Electrical, kWh (B)
1	1171.8	829.25	817	370.7	90	70
2	957.6	947.52	679	428.5	48	47.5
3	1159.2	1553.5	682	421.2	13	92.2
4	1719.9	828.1	1280	411.3	218	55.5
5	1751.4	842.6	1372	675.4	45	55.8
Total	**6759.9**	**5000.97**	**4830**	**2307.1**	**414**	**321**
Ave.	**1351.98**	**1000.19**	**966**	**461.42**	**82.8**	**64.2**

Note: A – Ventilation system; B – Dehumidified System

Curing Duration: Table 2 presents average curing durations. The shortest recorded curing dura-tion was 108 hours, significantly less than the standard 144 hours. Both ventilated and dehumidified SACB systems exhibited similar curing durations, though the dehumidified system required slightly more time. This suggests the need for a higher airflow rate in the suction fan for better moist air removal. However, a faster removal rate can reduce tobacco leaf body, leading to thinner cured leaves due to shrinkage. A balance between moisture removal rate and cured leaf quality is essential.

Table 2

Average tobacco curing duration of the different furnace and fuel source

Furnace	Fuel/ Energy Source	Curing Duration, hrs.
Anawang	Wood	144
Anawang	Wood + coconut husk/shell	110

Venturi	Wood	108
Modified	Wood	111
Modular	Wood	109
Solar Aided Curing barn		
Ventilated system	Wood + RE	108.6
Dehumidified system	Wood + RE	120.6
Total		**811.2**
Average		**115.88**

Drying Rate and Mass Reduction: Table 3 details average fresh weight (1.845 kg), cured weight (0.310 kg), drying rate (0.016 kg/hr.), and mass reduction (82.77%). The system can dry 2.3 kg of tobacco leaves over 144 hours at a constant temperature. These are general results, and further investigation is needed for specific drying rates at each curing stage due to optimal curing environment requirements.

Table 3
Average fresh and cured weight, drying rates and mass reductio of the sample tobacco leaves cured in the SACB dehumidified system

Curing no.	**Fresh Weight**	**Cured Weight**	**Drying Rates, kg/hr.**	**Mass Reduction, %**
1	1.659	0.15	0.021	90.96%
2	1.88	0.21	0.02	88.83%
3	2.39	0.335	0.018	86.00%
4	1.69	0.42	0.012	75.15%
5	1.605	0.435	0.011	72.90%
Total	**9.223**	**1.55**	**0.082**	**413.83%**
Mean	**1.845**	**0.31**	**0.016**	**82.77%**

Fuel to Cured Leaf Ratio (FCR): Table 4 presents the average FCR for different fuel sources. The SACB-Dehumidified system recorded the lowest FCR at 3.18. The SACB Ventilated system had a higher FCR at 5.04, compared to Anawang at 4.18. Other furnaces (Venturi, Modified Anawang, Modular Anawang) had FCRs of 3.85, 3.96, and 3.71, respectively. While Mpofu (2017) reported rocket barns using 2-3 kg firewood per kg of tobacco, the 3.18 FCR of the dehumidified system is still the lowest reported in the Philippines, despite the efficiency of clay brick rocket barns. This indicates the SACB-Dehumidified system is a step towards more efficient and sustainable tobacco curing.

Table 4

Average fuel to cured leaf ratio in tobacco flue-curing using different fuel sources

Furnace	Fuel Source	FCR	Ratio, % (wood: Other sources)
Anawang	Wood	4.18	
Anawang	Wood + coconut husk/shell	3.86	32.37:67.63
Venturi	Wood	3.85	
Modified	Wood	3.96	
Modular	Wood	3.71	
Solar Aided Curing barn			
Ventilated system	Wood + RE	5.04	92.23:7.77
Dehumidified system	Wood + RE	3.18	88.90:11.1

Correlation Analysis on Temperature vs. Fuelwood and Electricity Consumption: The cor- relation of increased temperature necessitates more frequent fuelwood feeding and higher electricity con- sumption. Solar energy utilization minimizes fuelwood consumption when available. Table 5 shows theaverage correlation coefficient for fuelwood vs. temperature is 0.340 (moderate positive correlation), meaning fuelwood consumption moderately increases with temperature. The average correlation coeffi- cient for solar electric vs. temperature is 0.112 (weak positive correlation), indicating a lesser impact on solar electric consumption. Variability suggests other factors influence consumption patterns, such as sunlight availability, management practices, and fuelwood type.

Table 5

Correlation coefficient of temperature versus fuelwood and solar energy consumption

Curing No.	Fuelwood vs. Temperature	Solar Electric vs. Temperature
1	0.008 *	0.055 *
2	0.643 ***	0.302 **
3	0.528 ***	0.122 *
4	0.461 **	0.044 *
5	0.059 *	0.035 *
Total	1.699	0.558
Mean	0.340*	0.112*

Note: * - Weak Positive Correlation; ** - Moderate Positive Correlation; *** - Strong Positive Correlation

Regression Analysis on Temperature versus fuelwood consumption: Regression analysis demonstrate a strong positive relationship between temperature and fuelwood consumption, where an increase in temperature leads to an increase in fuelwood consumption. The dehumidification system showed no significant difference in temperature and fuelwood consumption compared to the ventilated system. The regression model Y=0.143x predicts fuelwood consumption, with an 80-degree Celsius tem- perature resulting in 11.44 kg of fuelwood consumption. Table 7 shows a 28.75% difference between predicted and actual fuelwood consumption, indicating the significant impact of dehumidification. Future models should include factors related to the dehumidification system to precisely predict fuelwood con- sumption.

Environmental Impact: The projected environmental impacts of SACB–Ventilated System, SACB–Dehumidified System, and Anawang Furnace resulted to Dehumidified System uses less fuel- wood (kg/ha and m^3/ha), resulting in lower fuelwood costs. It also requires smaller forest areas and fewer trees, indicating a reduced impact on deforestation. Critically, it emits significantly less carbon than the Ventilated System, aligning with climate change mitigation efforts, and leading to lower annual carbon removal costs. The Dehumidified System is a more environmentally friendly and cost-effective solution, with implications for energy policy, especially in regions reliant on fuelwood for tobacco cultivation.

Conclusion

The integration of a dehumidification system into the SACB represents a significant advancement in tobacco curing technology, addressing inefficiencies and barriers of previous designs. By reducing fuelwood and electricity consumption, the system lowers operational costs and enhances environmental sustainability through minimized carbon emissions and deforestation impact. The economic analysis con- firms its cost-effectiveness and substantial ROI, offering farmers a viable path to improved profitabilityand sustainability. While advantageous, further airflow optimization for leaf quality and model refine- ment to include specific dehumidification factors affecting fuelwood consumption are important. These findings underscore the potential of the dehumidified SACB to revolutionize tobacco curing practices and provide a blueprint for sustainable agricultural innovation.

References

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