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Evaluation of integrated threshing and drying design concepts for paddy rice using analytical hierarchy process

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ABSTRACT

Threshing and drying are two major postharvest activities that contribute significantly to postharvest losses for small and medium-scale rice farmers, leading to food insecurity and hunger in Sub-Saharan Africa. Developing an appropriate system for threshing and drying needs urgent attention. The objective of the study involved the use of Analytical Hierarchy Process (AHP) for evaluation and selection of the best option among four design concepts for development and fabrication. The four design concepts shortlisted were: (1) batch flow biomass-powered manual threshing and drying system, (2) recirculating diesel-powered mobile threshing and drying system, (3) mechanized threshing with solar drying batch system, and (4) tractor-powered recirculating continues flow integrated system. For the MCAHP analysis, 17 attributes were proposed and divided into five main criteria. The evaluation of the main criteria showed that cost had the highest score, followed by performance, safety, ease of installation and operation, and manufacturability, with a global score of 0.560, 0.202, 0.108, 0.083 and 0.048, respectively. It was observed that design concept two received the highest weighted score of 0.35 and was selected as the design concept to proceed with. The consistency ratios of the main criteria and attributes were all less than 0.1, which is the allowable limit of inconsistency. In conclusion, concept 2 was selected as the best design for developing an integrated threshing and drying system for paddy rice and is recommended for development, fabrication, evaluation and optimisation.

Keywords: Multi-Criteria Analytical Hierarchy Process (MCAHP), Consistency ratio, Postharvest, Paddy rice, Integrated threshing and Drying system

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Introduction

Rice is the second most widely distributed crop in the world and is the staple food of approximately 50% of the world's population (Rahman and Zhang, 2022; Sharifan and Ma, 2021; Stoop *et al.*, 2002). By reducing unsuitable impurities during post-harvest operations, rice quality and quantity can be guaranteed, and this would significantly reduce losses (Zhang *et al.*, 2021). The need to reduce postharvest losses in Sub-Saharan Africa rice production continues to grow from year to year. When this need is addressed, there will be a sustainable method to increase the rice supply, eradicate hunger and improve livelihoods in developing nations (Saguy *et al.*, 2013; Sallaba *et al.*, 2017). This has called for engineers and researchers to design and develop threshing and drying systems that would make rice production less laborious. Developing more efficient post-harvest technologies for threshing, drying and winnowing rice for smallholder farmers is crucial for reducing post-production losses (Sutardi *et al.*, 2022).

The success of designing and developing appropriate threshing and drying systems for rice production depends on the optimal evaluation and selection of suitable design concepts based on engineering design criteria and their corresponding attributes (Liu *et al.*, 2023).

Several methods have been developed for concept evaluation and selection, including Pugh's method, Decision Matrix, Cost-Benefit Analysis, SWOT Analysis, Multi-Criteria Analytic Hierarchy Process (AHP), etc. (Butt and Jedi, 2020; Masood *et al.*, 2004; Turečková and Nevima, 2020; Shvetsova *et al.*, 2021; Obeng-Akrofi *et al.*, 2022; Armah *et al.*, 2021). The choice of evaluation method during the concept selection process profoundly affects the level of success of product development (Liu *et al.*, 2023). This research focuses on the use of AHP for the evaluation and selection of the design concept. Several researchers have used the AHP for design concept evaluation, engineering problem decomposition and multicriteria decision-making (Mimović *et al.*, 2015; Aly and Vrana, 2008; Madzík and Falat; 2022).

This research aims to evaluate and select the best and appropriate design concept for developing an integrated threshing and drying system for paddy rice for small and medium-scale farmers.

Materials and Methods

Overview of Multi-Criteria AHP

This methodology describes in detail the approach used in developing the evaluation and selection of the concept in this case study. The Analytical Hierarchy Process is a well-established multicriteria decision-making methodology developed by Saaty in the 1970s to streamline intricate multi-criteria decision making and concept evaluations (Mazurek *et al.*, 2021). This process is based on a Weighted Sum Model (WSM) or Weighted Score Model, in which alternatives are compared and evaluated based on a relevant set of multiple criteria and attributes represented through their relative importance (Howari *et al.*, 2023). To facilitate this methodical decision-making process, the identified criteria are divided into a hierarchy of criteria, attributes and alternatives (Ortega *et al.*, 2021). The hierarchical system, pairwise comparisons, and preference aggregation help to clarify the decision-making logic and enable examinations among engineers and researchers during concept evaluation and selection. This approach is a preference-based prioritization of multi-criteria and alternatives, allowing for a more thorough evaluation of the decision alternatives and has been widely used by many engineering research and professional fields (Akintayo *et al.*, 2023).

Case Study: Using AHP for design concept evaluation and selection of paddy rice integrated threshing and drying

For this work, the following steps were followed in using AHP for design concept evaluation and selection of paddy rice integrated threshing and drying:

- Definition of the overall objective of the evaluation
- Identification of criteria, attributes and alternative design concepts for the system
- Development of a structured hierarchy framework for analysis
- Performance of a pairwise comparison judgment for each level
- Conducting priority synthesis of the matrix
- Evaluation of the consistency of each comparison matrix
- Rank the alternatives and select the concept with the highest overall score

Define the overall objective of the evaluation

The objective of the study is to evaluate and select the most appropriate design concept for the development of an integrated threshing and drying system for paddy rice.

Identify criteria, attributes and alternative design concepts for the system

In this paper, AHP was applied to evaluate and select the best design concept for developing an integrated threshing and drying system for paddy rice. Several ideations using the design and product development cycle generated four design concepts for integrated threshing and drying.

To differentiate among the alternative concepts, five selection criteria have been defined based on customer requirements and engineering literature (Shi *et al.*, 2023; Kraiem *et al.*, 2023). The selections criteria are performance, cost, safety, and manufacturability, and ease of installation and operation (Butt and Jedi, 2020; Juniani *et al.*, 2022; Snyder *et al.*, 2006; Roxas *et al.*, 2023). These five concepts were further divided into seventeen (17) product attributes, which were:

1. Capacity
2. Ease of Mobility
3. Ease of Use
4. Energy Efficiency
5. Ergonomics
6. Inspection Repairs and Maintenance (IRM)
7. Load Bearing Capabilities (LBC)
8. Material Availability and Selection (MAS)
9. Noise and Vibration Levels (NVL)
10. Operating Cost
11. Operation Efficiency
12. Operator Training and Instructions (OTI)
13. Production Cost
14. Safety Features
15. Simplicity of Design
16. Standardization of Parts
17. Tools and Equipment Requirement (TER)

The four generated concepts were (1) batch flow biomass-powered manual threshing and drying system, (2) recirculating diesel-powered mobile threshing and drying system (3) mechanized threshing with solar drying batch system and (4) tractor-powered recirculating continuous flow integrated system; which are discussed below.

Concept 1 is a threshing and drying system that uses biomass materials as the energy source and operates in batches. The system comprises a threshing machine, a dryer, and a manual transfer system for moving the threshed grain from the threshing machine to the dryer (Susanto *et al.*, 2021; Borowski, 2022). The threshing process involves separating the paddy rice from the straw using a threshing machine, such as a traditional manual or mechanized thresher. The threshed grain is then collected in a hopper of the dryer. The drying process involves removing moisture from the threshed grain using a mechanized dryer. The dryer uses heat from burning biomass materials, such as rice straw, and wood chips, to dry the grain (Obeng-Akrofi *et al.*, 2021). The dried grain is then allowed to cool and stored.

This system is designed for small-scale farmers, who may not have the resources to invest in a large, industrial threshing and drying system. It can be useful for farmers who have easy access to biomass materials and want to use agricultural wastes. However, this system may require more labour and time as the manual transfer of the paddy rice is needed, and it may also depend on the availability of biomass materials. It may have environmental implications due to emissions from burning biomass. It also may not be as efficient as other models regarding time and labour and may require more maintenance to keep the threshing and drying equipment in good working condition.

Concept 2 is a threshing and drying system that combines the functions of threshing and drying into a single mobile unit. The system is powered by a diesel engine, which provides the power for the threshing process and the motors that run the drying unit. The heat for the drying process is by an LPG (liquid petroleum gas) (Dębowski *et al.*, 2021). The threshing is a mechanized process that involves separating the grain from the straw using a threshing drum. The threshed grain is then conveyed into the hopper of the drying unit. The drying process consists in reducing the moisture of the threshed paddy rice in the recirculating twin dryer. The hot air generated from burning LPG is blown into the plenum of the drying unit to dry the paddy rice. LPG is a clean-burning fuel that is considered more environmentally friendly than other fossil fuels. One key feature of this system is that it is mobile, which means it can be easily moved from one farm to another. This can be particularly useful for small-scale farmers who may not have the resources to invest in a stationary threshing and drying system (Amponsah *et al.*, 2017; Xue *et al.*, 2021; Sims and Kienzle, 2016). Another key feature of this system is that it recirculates the paddy rice in the drying chamber until the desired moisture content is achieved (Van Hung *et al.*, 2018). This system can be useful for farmers, who want to reduce labour and time required for threshing and drying, as well as reduce the costs associated with operating a stationary system. The use of LPG as a heat source may reduce emissions compared to other fossil fuels and can be a more environmentally friendly option. However, it's important to note that this type of system may require more maintenance and fuel consumption than other models.

Concept 3 is a threshing and drying system that uses solar energy as the energy source and it operates in batches. The system comprises a mechanized threshing machine, a solar dryer, and a manual transfer system for moving the threshed grain from the threshing machine to the dryer. The threshing process involves separating the grain from the straw using a mechanized thresher (Amponsah *et al.*, 2017; Xue *et al.*, 2021; Sims and Kienzle, 2016). The threshed grain is then collected in a hopper or container. The drying process involves reducing the moisture of the paddy rice using a solar dryer (Kotey *et al.*, 2022; Lamidi *et al.*, 2019; Akowuah *et al.*, 2021).

This system is designed for small-scale farmers who may not have the resources to invest in a large industrial threshing and drying system. It can be for farmers with easy access to solar energy and want to minimize the environmental impact. However, it is important to note that this system may require more labour and time as manual transfer of the rice is needed and it is dependent on the availability of sunlight. In addition, the drying process may take longer than other models, especially during periods of low sunlight or overcast weather (Weng *et al.*, 2017; Ahmad *et al.*, 2022). It also may require more maintenance to keep the threshing and drying equipment in good working condition.

Concept 4 uses a tractor to power the threshing and drying processes. This system is mainly for large-scale operations and is composed of a threshing machine, a dryer, and a conveyor belt system for moving the threshed paddy rice from the threshing unit into the drying unit (Paman *et al.*, 2016; Gummert *et al.*, 2020). The threshing process involves separating the paddy rice from the straw using a mechanical threshing machine, such as a combine harvester or a threshing drum. A conveyor belt then transports the threshed grain to the dryer that uses heated air to dry the grain.

Develop a structured hierarchy framework for analysis

The AHP is a mechanism where a complex decision model is simplified into a hierarchy with the expected goal of the decision being placed at the extreme left beginning the process and the alternative concepts at the extreme right to the lowest level of the hierarchy (Wu *et al.*, 2023). To decompose the decision problems of choosing the best design concept of integrated threshing and drying, four levels of hierarchy structure are created, as shown in Figure 1. The criteria and attributes that affect the decision are placed at the intermediate levels between the expected goal and the alternative concepts. This decision-making approach provides an apparent disintegration to better explain the purpose of the concept selection process based on the existing alternatives (Singh *et al.*, 2019). Figure 1 furthers all the attributes under each criterion in achieving our expected goal. Table 1 maps out the various concept criteria and their corresponding attributes. In total there are seventeen attributes and five concept criteria. Criterion 1 had attributes 1 to 4, 7 and 11, criterion 2 had attributes 6, 10, 12 and 13, criterion 3 had attributes 5, 6, 9, 12 and 14, criterion 4 had attributes 8 and 15 to 17 and criterion 5 had attributes 5, 12, 14 and 17.

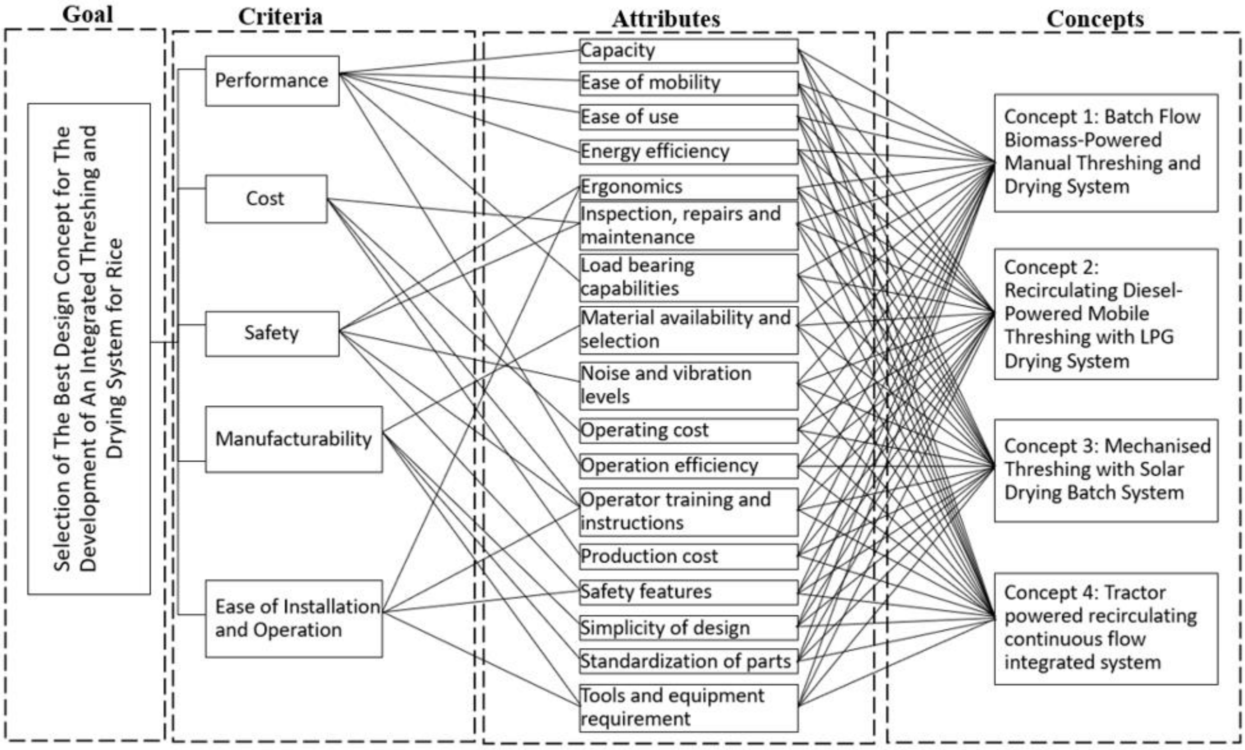

Fig. 1. Horizontal hierarchy structure for the evaluation of integrated threshing and drying design concepts

Perform Pairwise Comparison Judgments for each level

After the development of structural hierarchy, a pairwise comparison is performed at criteria, attributes and concept levels to determine the priorities of elements at each stage. In a set of pairwise comparison matrices at the criteria level; performance, cost, safety and ease of installation and operation, each criterion is compared with one another to determine their level of importance. A similar approach is performed at the attribute and the concept levels to assess the significance of the elements at each level. Table 2 shows the fundamental scale developed by Thomas Saaty, which consists of a series of numerical values that decision-makers use to express their preferences pair wisely. The scale accommodates positive and negative judgments, providing a consistent framework for capturing subjective assessments. This fundamental scale is a crucial component of the AHP methodology, allowing decision-makers to systematically and quantitatively assess and prioritize criteria and alternatives. This approach of comparison results in allocating the numerical weight of importance to each criterion (Saaty and Mu, 2022).

Table 1. Mapping of concept criteria to product attributes for integrated threshing and drying system.

		Design Criteria				
No.	Attribute	C_1	C_2	C_3	C_4	C_5
1	A_1	x				
2	A_2	x				
3	A_3	x				
4	A_4	x				
5	A_5			x		x
6	A_6		x	x		
7	A_7	x				
8	A_8				x	
9	A_9			x		
10	A_{10}		x			
11	A_{11}	x				
12	A_{12}		x	x		x
13	A_{13}		x			
14	A_{14}			x		x
15	A_{15}				x	
16	A_{16}				x	
17	A_{17}				x	x

Table 2. Fundamental Scale of Thomas L. Saaty (Saaty and Mu, 2022).

Intensity of importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the property
3	Moderate importance of one over another	Experience and judgment slightly favour one over the other
5	Essential importance or strong	Experience and judgment strongly favour one over another
7	Of very high importance strong	An element is strongly favoured and its dominance is demonstrated in practice.
9	Of extreme importance	The evidence favouring one element over another is one of the highest possible orders of affirmation
2,4,6,8	Intermediate values between two adjacent judgments	Compromise is needed between two judgments
Reciprocals	When activity *i* compared to *j* is assigned one of the above numbers, the activity j compared to is assigned its reciprocal	
Rational	Ratios arising from forcing consistency of judgments	

Table 3. Model of matrix containing weights for concept evaluation.

Criteria	a_1	a_2	a_3	…	a_n
a_1	w_1/w_1	w_1/w_2	w_1/w_3	…	w_1/w_n
a_2	w_2/w_1	w_2/w_2	w_2/w_3	…	w_2/w_n
	w_3/w_1	w_3/w_2	w_3/w_3	…	w_3/w_n
⋮	⋮	⋮	⋮		⋮
a_n	w_1/w_1	w_1/w_2	w_1/w_3	…	w_1/w_n

Conducting priority synthesis of the matrix

To conduct a priority synthesis for each criterion in the matrix, the individual aggregates are normalized by dividing the aggregate value by the vertical sum. The horizontal average of the normalized aggregates becomes the criteria weight or priority vector for each criterion. Each criterion weight is vertically multiplied by its corresponding original aggregate. The horizontal sum of the product of the criteria weight and the original aggregate become the weighted sum for each matrix criterion.

Evaluation of consistency of each comparison matrix

To evaluate the consistency of the comparison matrix, the consistency rate (CR) has to be calculated (Dodevska *et al.*, 2023). The CR is defined as a ratio of the consistency index (CI) and the random consistency index (RCI). The consistency rate (CR) is the maximum allowable inconsistency that should not be exceeded is 0.1. The closer the value is to zero, the more consistent the matrix. The random consistency index depends on the matrix size (n). Table 4 shows the size of matrix and their corresponding RCI values. The Consistency Index (CI) is calculated using the formula as in Equation 1, where λmax is the maximum Eigen value (λmax) and n the matrix size. The maximum Eigen value of a matrix refers to the largest Eigen value associated with that matrix (Cheng *et al.*, 2002; Liang *et al.*, 2023). This is the product of the weighted sum and the priority of each criterion or attribute of a matrix.

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \qquad (1)$$

$$CR = {}^{CI}/_{RCI} \qquad (2)$$

Table 3. Model of matrix containing weights for concept evaluation.

Size of Matrix (n)	Random Consistency Index (RCI)
1	0
2	0
3	0.52
4	0.89
5	1.11
6	1.25
7	1.35
8	1.40
9	1.45
10	1.49

Ranking of alternatives and selection of concept with the highest overall score

To rank the alternative concepts, the criterion weight is multiplied by the attribute weight and the concept priority vector to give the weighted concept score (Cheng *et al.*, 2002; Liang *et al.*, 2023). The weighted score under each concept is summed together to provide the total weighted concept score, which becomes the priority score for each alternative design concept (Zhuang *et al.*, 2018).

Therefore, the best alternative design concept is the one with the highest value after the summation of the product of the weight of each criterion (Wc), the weight of each attribute (Wa) and their corresponding concept priority vector (PVcn). Equation 3 as used by Liang *et al.* (2023), explains how the alternative concepts were ranked and the best alternative was selected as shown in Table 19.

Concept Score is represented by;

$$Z_{Cpt_n} = \sum_{x}^{1} (W_c \times W_a \times P_{vcn}) \qquad (3)$$

Where,

W_c is the Concept of weight
W_a is the Attribute weight
P_{vcn} in the number of concept Priority Vector
Z_{Cptn} is the Total weighted score for each alternative design concept
x is the number of attributes closest in the hierarchy to the alternative design concepts

Results and Discussion

Priority synthesis of criteria and attributes matrices

In conducting a priority synthesis of the criteria, a pairwise comparison between all criteria was conducted as shown in Table 5 (Wardana and Rianto, 2021). The aggregate of each criterion was based on customer requirements, technological knowledge and general engineering literature and theories focusing on the overall objective, which was to evaluate and select design concepts for the development of an integrated threshing and drying system for paddy rice. Researchers and engineers from different disciplines of studies have applied this approach in some applicable studies (Shvetsova *et al.*, 2021; Rao and Patel, 2010; Maputi and Arora, 2020; Sianturi and Wijaya, 2019). In this study, considering the scale from Table 5, a score of 3 is given to C2 compared to C1. Following the AHP technique in generating a pairwise comparison matrix, C1 will be compared to C2 by 1/3. Each criterion in comparison to itself is 1, making all the diagonal scores for all the pairwise comparison matrix for both the requirements and the attributes 1 (Falavigna *et al.*, 2021). Similar technique was used in generating a pairwise comparison matrix for all the attributes, as shown in Table 6 to Table 10.

Table 5. Pairwise comparison of concept criteria concerning overall goal.

	Concept Criteria				
	C_1	C_2	C_3	C_4	C_5
C_1	1	1/3	2	4	3
C_2	3	1	6	9	8
C_3	1/2	1/6	1	2	2
C_4	1/4	1/9	1/2	1	1/3
C_5	1/3	1/8	1/2	3	1
Sum	5.083	1.736	10.0	19.0	14.33

Table 5 shows the pairwise comparison of the concept criteria concerning the overall goal of evaluation and selection of the best design concept for developing an integrated threshing and drying system for rice.

Table 6. Pairwise comparison of product attributes concerning performance.

	Performance Attributes					
	A_1	A_2	A_3	A_4	A_7	A_{11}
A_1	1	4	3	1/2	4	1/3
A_2	1/4	1	1/2	1/8	1	1/9
A_3	1/3	2	1	1/6	2	1/8
A_4	2	8	6	1	8	1/2
A_7	1/4	1	1/2	1/8	1	1/9
A_{11}	3	9	8	2	9	1
Sum	6.83	25.0	19.0	3.92	25.0	2.18

Table 6 shows the pairwise comparison for evaluation of the seven attributes concerning performance. The performance is one of the criteria for evaluating and selecting the design concept.

Table 7. Pairwise comparison of product attributes to cost.

	Cost Attributes			
	A_6	A_{10}	A_{12}	A_{13}
A_6	1	3	6	7
A_{10}	1/3	1	2	2
A_{12}	1/6	1/2	1	2
A_{13}	1/7	1/2	1/2	1
Sum	1.64	5.0	9.5	12.0

Table 7 shows the pairwise comparison for the evaluation of the four attributes with respect to cost, which is one of the criteria for evaluating and selecting the design concept.

Table 8. Pairwise comparison of product attributes to safety.

	Safety Attributes				
	A_5	A_6	A_9	A_{12}	A_{14}
A_5	1	2	4	7	7
A_6	1/2	1	2	4	4
A_9	1/4	1/2	1	2	2
A_{12}	1/7	1/4	1/2	1	1
A_{14}	1/7	1/4	1/2	1	1
Sum	2.036	4.0	8.0	15.0	15.0

Safety is one of the criteria for evaluating and selecting the design concept. Table 8 shows the pairwise comparison used to assess the five attributes of safety.

Table 9. Pairwise comparison of product attributes to manufacturability.

	Manufacturability Attributes			
	A_8	A_{15}	A_{16}	A_{17}
A_8	1	3	3	7
A_{15}	1/3	1	1	2
A_{16}	1/3	1	1	2
A_{17}	1/7	1/2	1/2	1
Sum	1.81	5.5	5.5	12.0

Table 9 shows the pairwise comparison for the evaluation of the four attributes to manufacturability. Manufacturability is one of the criteria for evaluating and selecting the design concept.

Table 10. Pairwise comparison of product attributes to ease of installation and operation.

	Attributes for Installation and Operation			
	A_5	A_{12}	A_{14}	A_{17}
A_5	1	4	2	6
A_{12}	1/4	1	1/2	2
A_{14}	1/2	2	1	4
A_{17}	1/6	1/2	1/4	1
Sum	1.92	7.5	3.75	13.0

Table 10 shows the pairwise comparison for evaluation of the four attributes concerning ease of installation and operation, which is one of the criteria for evaluating and selecting the design concept. From the evaluation, cost (C_2) had the highest priority score of 0.56 as shown in Figure 2. Performance (C_1), safety (C_3), ease of installation and operation (C_5) and manufacturability (C_4) had priority score of 0.202, 0.108, 0.083 and 0.048, respectively as shown in Figure 2. This is a logical conclusion for the target group of small and medium-scale farmers, who consider the cost of a technology as their number one major concern, followed by performance.

Consistency checks of the comparison matrix

Considering the human factor in decision-making through scales, verifying the consistency of the scores allocated to every comparison was important. The consistency check used in the analytical hierarchy process ensures coherence in the assigned scores for each pairwise comparison matrix (Luqman *et al.*, 2018; Liu *et al.*, 2019). For each size of matrix, a corresponding random consistency index (RCI) is assigned as shown in Table 4 and used in Table 11. With the five criteria considered in the study, the assigned RCI was 1.11 (Liang *et al.*, 2023). The maximum Eigen value for the decision criteria matrix was calculated to be 5.14, resulting in a Consistency Index of 0.0344. A Consistency Ratio (CR) of 0.0307 was determined from Equations (1) and (2) as shown in Table 11. Since the consistency ratio was less than 0.1 it is acceptable because the maximum allowable inconsistency (CR) should not exceed 10% (Dodevska *et al.*, 2023).

Similar consistency checks were conducted on all the attributes and alternative concepts comparison matrices. It was evident that their consistency indices were less than 0.1 as shown in Table 12 to Table 18.

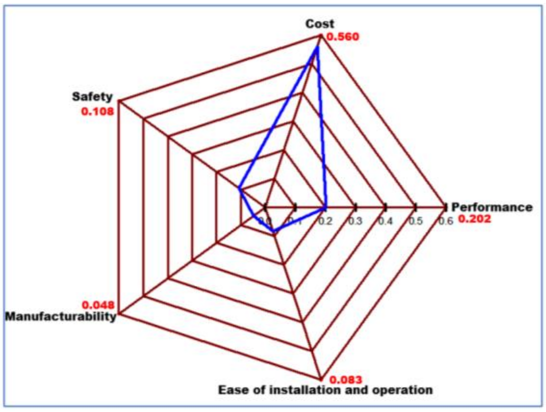

Fig. 2. Priorities of criteria in the selection of an appropriate design concept.

Table 11. Priority synthesis and consistency evaluation of concept criteria with respect to the overall goal.

Goal	C_1	C_2	C_3	C_4	C_5	Weighted Sum	Priority	Ratio of WS/ Priority (λ_{max})
C_1	0.202	0.187	0.216	0.191	0.249	1.04	0.202	5.18
C_2	0.605	0.560	0.647	0.430	0.664	2.91	0.560	5.19
C_3	0.101	0.093	0.108	0.096	0.166	0.56	0.108	5.23
C_4	0.050	0.062	0.054	0.048	0.028	0.24	0.048	5.06
C_5	0.067	0.070	0.054	0.143	0.083	0.42	0.083	5.03
	Total (Σ) =							25.69
	Maximum Eigen Value(λ_{max}) =							5.14
	n=5, IR=1.12, $CI = \frac{(\lambda_{max}-n)}{(n-1)}$, $CI = 0.0344$, $CR = {CI}/{RCI}$ $CR = 0.0307$, Acceptable because CR=0.0307<0.1							

Table 12. Priority synthesis and consistency evaluation of product attributes for performance.

C_1	A_1	A_2	A_3	A_4	A_7	A_{11}	Weighted Sum	Priority	Ratio of WS/ Priority (λ_{max})
A_1	0.151	0.151	0.181	0.144	0.151	0.142	0.92	0.151	6.09
A_2	0.038	0.038	0.030	0.036	0.038	0.047	0.23	0.038	6.02
A_3	0.050	0.075	0.060	0.048	0.075	0.053	0.36	0.060	6.02
A_4	0.302	0.301	0.361	0.289	0.301	0.212	1.77	0.289	6.11
A_7	0.038	0.038	0.030	0.036	0.038	0.047	0.23	0.038	6.02
A_{11}	0.452	0.339	0.482	0.578	0.339	0.425	2.61	0.425	6.15
								Total (Σ) =	36.41
								Maximum Eigen Value(λ_{max}) =	6.068
	n=6, IR=1.25, $CI = \frac{(\lambda_{max}-n)}{(n-1)}$, $CI = 0.0135$, $CR = {CI}/{RCI}$ $CR = 0.0109$, Acceptable because CR=0.0109<0.1								

Table 13. Priority synthesis and consistency evaluation of product attributes for cost.

C_2	A_6	A_{10}	A_{12}	A_{13}	Weighted Sum	Priority	Ratio of WS/ Priority (λ_{max})
A_6	0.606	0.585	0.710	0.565	2.47	0.606	4.07
A_{10}	0.202	0.195	0.237	0.161	0.80	0.195	4.08
A_{12}	0.101	0.098	0.118	0.161	0.48	0.118	4.04
A_{13}	0.087	0.098	0.059	0.081	0.32	0.081	4.01
						Total (Σ)=	16.20
						Maximum Eigen Value(λ_{max}) =	4.050
	n=4, IR=0.90, $CI = \frac{(\lambda_{max}-n)}{(n-1)}$, $CI = 0.016$, $CR = {CI}/{RCI}$ $CR = 0.0187$, Acceptable because CR=0.0187<0.1						

Table 14. Priority synthesis and consistency evaluation of product attributes for safety.

C_3	A_5	A_6	A_9	A_{12}	A_{14}	Weighted Sum	Priority	Ratio of WS/ Priority (λ_{max})
A_5	0.485	0.512	0.512	0.460	0.460	2.43	0.485	5.01
A_6	0.242	0.256	0.256	0.263	0.263	1.28	0.256	5.00
A_9	0.121	0.128	0.128	0.131	0.131	0.64	0.128	5.00
A_{12}	0.069	0.064	0.064	0.066	0.066	0.33	0.066	5.00
A_{14}	0.069	0.064	0.064	0.066	0.066	0.33	0.066	5.00
							Total (Σ) =	25.01
							Maximum Eigen Value(λ_{max}) =	5.003
	n=5, IR=1.12, $CI = \frac{(\lambda_{max}-n)}{(n-1)}$, $CI = 0.0007$, $CR = {CI}/{RCI}$ $CR = 0.000637$, Acceptable because CR=0.000637<0.1							

Table 15. Priority synthesis and consistency evaluation of product attributes for manufacturability.

C_4	A_8	A_{15}	A_{16}	A_{17}	Weighted Sum	Priority	Ratio of WS/ Priority (λ_{max})
A_8	0.557	0.536	0.536	0.602	2.23	0.557	4.01
A_{15}	0.186	0.179	0.179	0.172	0.71	0.179	4.00
A_{16}	0.186	0.179	0.179	0.172	0.71	0.179	4.00
A_{17}	0.080	0.089	0.089	0.086	0.34	0.086	4.00
						Total (Σ)=	16.01
						Maximum Eigen Value(λ_{max}) =	4.003
	n=4, IR=0.90, $CI = \frac{(\lambda_{max}-n)}{(n-1)}$, $CI = 0.001$, $CR = {CI}/{RCI}$ $CR = 0.0011$, Acceptable because CR=0.0011<0.1						

Table 16. Priority synthesis and consistency evaluation of product attributes for ease of installation and operation.

C_5	A_5	A_{12}	A_{14}	A_{17}	Weighted Sum	Priority	Ratio of WS/ Priority (λ_{max})
A_5	0.512	0.551	0.551	0.446	2.06	0.512	4.02
A_{12}	0.128	0.138	0.138	0.149	0.55	0.138	4.01
A_{14}	0.256	0.275	0.275	0.297	1.10	0.275	4.01
A_{17}	0.085	0.069	0.069	0.074	0.30	0.074	4.00
	Total (Σ)=						16.04
	Maximum Eigen Value(λ_{max}) =						4.010
	n=4, IR=0.90, $CI = \frac{(\lambda_{max}-n)}{(n-1)}$, $CI = 0.0035$, $CR = {CI}/{RCI}$ $CR = 0.0038$, Acceptable because CR=0.0038<0.1						

Table 17. Priority synthesis and consistency evaluation of attributes A_1 to A_9.

Attribute	Concepts	Weight Sum (W_c)	Concept Priority Vector (PV_c)	Consistency Test Results (where n=4, I.R.=0.9)
A_1	Cpt_1	0.272	0.067	$CI = 0.0163$ $CR = 0.0181$ Acceptable because CR=<0.1
	Cpt_2	1.568	0.387	
	Cpt_3	0.941	0.233	
	Cpt_4	1.269	0.313	
A_2	Cpt_1	0.421	0.105	$CI = 0.000$ $CR = 0.000$ Acceptable because CR=<0.1
	Cpt_2	1.684	0.421	
	Cpt_3	0.211	0.053	
	Cpt_4	1.684	0.421	
A_3	Cpt_1	0.359	0.089	$CI = 0.0083$ $CR = 0.0092$ Acceptable because CR=<0.1
	Cpt_2	1.969	0.488	
	Cpt_3	0.764	0.190	
	Cpt_4	0.934	0.233	
A_4	Cpt_1	2.001	0.474	$CI = 0.00727$ $CR = 0.0808$ Acceptable because CR=<0.1
	Cpt_2	0.480	0.114	
	Cpt_3	1.452	0.329	
	Cpt_4	0.333	0.082	
A_5	Cpt_1	2.279	0.563	$CI = 0.00153$ $CR = 0.0170$ Acceptable because CR=<0.1
	Cpt_2	0.853	0.210	
	Cpt_3	0.561	0.140	
	Cpt_4	0.357	0.088	
A_6	Cpt_1	2.766	0.687	$CI = 0.0035$ $CR = 0.0038$ Acceptable because CR=<0.1
	Cpt_2	0.494	0.123	
	Cpt_3	0.494	0.123	
	Cpt_4	0.266	0.066	
A_7	Cpt_1	0.266	0.066	$CI = 0.0014$ $CR = 0.0015$ Acceptable because CR=<0.1
	Cpt_2	1.456	0.363	
	Cpt_3	0.761	0.190	
	Cpt_4	1.522	0.380	
A_8	Cpt_1	2.224	0.542	$CI = 0.0171$ $CR = 0.0190$ Acceptable because CR=<0.1
	Cpt_2	0.947	0.233	
	Cpt_3	0.561	0.140	
	Cpt_4	0.341	0.085	
A_9	Cpt_1	2.480	0.598	$CI = 0.0220$ $CR = 0.0245$ Acceptable because CR=<0.1
	Cpt_2	0.305	0.076	
	Cpt_3	0.496	0.123	
	Cpt_4	0.826	0.203	

Table 18. Priority synthesis and consistency evaluation of attributes A_{10} to A_{17}.

Attribute	Concepts	Weight Sum (W_c)	Concept Priority Vector (PV_c)	Consistency Test Results (where n=4, I.R.=0.9)
A_{10}	Cpt_1	0.193	0.048	$CI = 0.0069$ $CR = 0.0077$ Acceptable because CR=<0.1
	Cpt_2	2.007	0.497	
	Cpt_3	0.669	0.167	
	Cpt_4	1.159	0.287	
A_{11}	Cpt_1	0.304	0.076	$CI = 0.0035$ $CR = 0.0038$ Acceptable because CR=<0.1
	Cpt_2	1.967	0.489	
	Cpt_3	0.608	0.152	
	Cpt_4	1.135	0.283	
A_{12}	Cpt_1	2.766	0.687	$CI = 0.0035$ $CR = 0.0038$ Acceptable because CR=<0.1
	Cpt_2	0.494	0.123	
	Cpt_3	0.494	0.123	
	Cpt_4	0.266	0.066	
A_{13}	Cpt_1	0.236	0.059	$CI = 0.0055$ $CR = 0.0061$ Acceptable because CR=<0.1
	Cpt_2	2.059	0.513	
	Cpt_3	1.080	0.269	
	Cpt_4	0.641	0.160	
A_{14}	Cpt_1	2.260	0.556	$CI = 0.0103$ $CR = 0.0115$ Acceptable because CR=<0.1
	Cpt_2	0.316	0.079	
	Cpt_3	0.547	0.137	
	Cpt_4	0.923	0.229	
A_{15}	Cpt_1	2.394	0.596	$CI = 0.0038$ $CR = 0.0042$ Acceptable because CR=<0.1
	Cpt_2	0.275	0.069	
	Cpt_3	0.861	0.214	
	Cpt_4	0.485	0.121	
A_{16}	Cpt_1	1.699	0.423	$CI = 0.0035$ $CR = 0.0038$ Acceptable because CR=<0.1
	Cpt_2	0.911	0.227	
	Cpt_3	0.911	0.227	
	Cpt_4	0.491	0.123	
A_{17}	Cpt_1	1.856	0.459	$CI = 0.0153$ $CR = 0.0170$ Acceptable because CR=<0.1
	Cpt_2	0.581	0.144	
	Cpt_3	0.914	0.226	
	Cpt_4	0.694	0.171	

Model synthesis and preference selection of alternative concept

The relative weight of the alternative design concepts based the attributes was synthesize by developing the priority weight for the concepts' matrix (Li *et al.*, 2023). The local priority of each concept is determined by finding the average of the normalized pairwise comparison for the matrix (Bureš *et al.*, 2020). The weighted score is multiplied by the local priority and summed up to determine the overall score for each alternative concept.

Overall, Concept 2, which is the recirculating diesel-powered mobile threshing with LPG drying system, had the highest total weighted score of 0.35, followed by Concept 1 the batch flow biomass-powered manual threshing and drying system, Concept 3 mechanized threshing with solar drying batch system, and Concept 4 the tractor powered recirculating continuous flow integrated system with weighted score of 0.28, 0.20, and 0.17, respectively is shown in Figure 3. Table 19.

Table 19. Overall ranking and selection of alternative design concepts.

		Criteria and Attribute Weights		Concept Priority Vector				Concept Score (W_c x W_a x PV_{cn})			
Criteria	Attribute	W_c	W_a	PV_{c1}	PV_{c2}	PV_{c3}	PV_{c4}	Cpt_1	Cpt_2	Cpt_3	Cpt_4
C_1	A_1	0.202	0.151	0.067	0.387	0.233	0.313	0.0020	0.0118	0.0071	0.0095
	A_2	0.202	0.038	0.105	0.421	0.053	0.421	0.0008	0.0032	0.0004	0.0032
	A_3	0.202	0.060	0.089	0.488	0.190	0.233	0.0011	0.0059	0.0023	0.0028
	A_4	0.202	0.289	0.474	0.114	0.329	0.082	0.0276	0.0067	0.0192	0.0048
	A_7	0.202	0.038	0.066	0.363	0.190	0.380	0.0005	0.0028	0.0014	0.0029
	A_{11}	0.202	0.425	0.076	0.489	0.152	0.283	0.0065	0.0419	0.0130	0.0243
C_2	A_6	0.560	0.606	0.059	0.513	0.269	0.160	0.0199	0.1738	0.0911	0.0542
	A_{10}	0.560	0.195	0.048	0.497	0.167	0.287	0.0053	0.0543	0.0182	0.0314
	A_{12}	0.560	0.118	0.687	0.123	0.123	0.066	0.0455	0.0082	0.0082	0.0044
	A_{13}	0.560	0.081	0.687	0.123	0.123	0.066	0.0310	0.0056	0.0056	0.0030
C_3	A_5	0.108	0.485	0.563	0.210	0.140	0.088	0.0294	0.0110	0.0073	0.0046
	A_6	0.108	0.256	0.598	0.076	0.123	0.203	0.0165	0.0021	0.0034	0.0056
	A_9	0.108	0.128	0.556	0.079	0.137	0.229	0.0077	0.0011	0.0019	0.0032
	A_{12}	0.108	0.066	0.687	0.123	0.123	0.066	0.0049	0.0009	0.0009	0.0005
	A_{14}	0.108	0.066	0.687	0.123	0.123	0.066	0.0049	0.0009	0.0009	0.0005
C_4	A_8	0.048	0.557	0.596	0.069	0.214	0.121	0.0159	0.0018	0.0057	0.0032
	A_{15}	0.048	0.179	0.542	0.233	0.140	0.085	0.0046	0.0020	0.0012	0.0007
	A_{16}	0.048	0.179	0.423	0.227	0.227	0.123	0.0036	0.0019	0.0019	0.0010
	A_{17}	0.048	0.086	0.459	0.144	0.226	0.171	0.0019	0.0006	0.0009	0.0007
C_5	A_5	0.083	0.512	0.563	0.210	0.140	0.088	0.0239	0.0089	0.0059	0.0038
	A_{12}	0.083	0.138	0.459	0.144	0.226	0.171	0.0052	0.0016	0.0026	0.0020
	A_{14}	0.083	0.275	0.556	0.079	0.137	0.229	0.0127	0.0018	0.0031	0.0052
	A_{17}	0.083	0.074	0.687	0.123	0.123	0.066	0.0042	0.0008	0.0008	0.0004
					Total Weighted Score			0.28	0.35	0.20	0.17
					Ranking			2	1	3	4

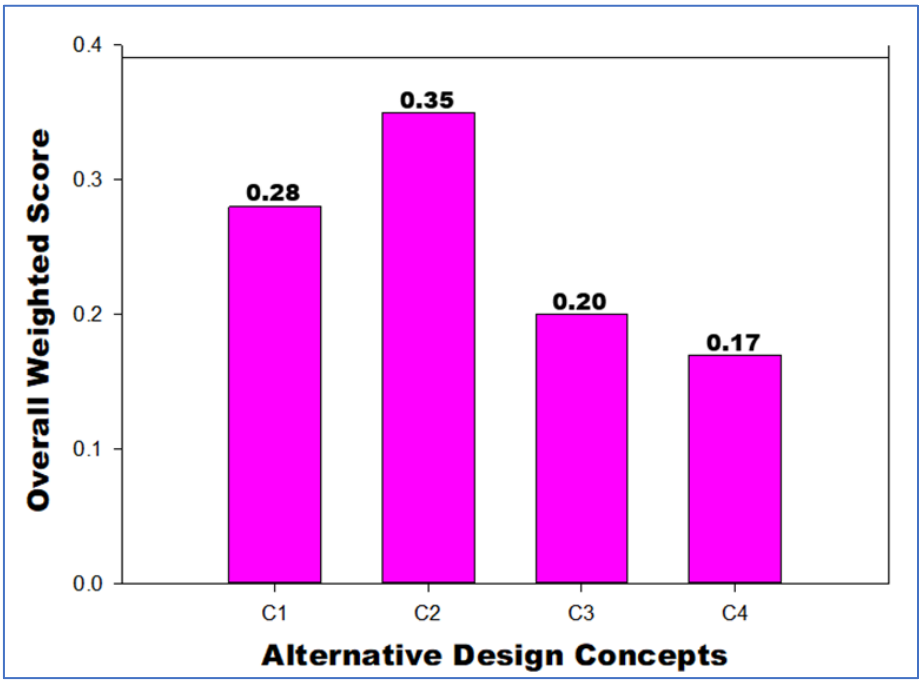

Fig. 3. Model synthesis for the selection of the appropriate design concept.

Conclusions

This study conducted a comprehensive evaluation of integrated threshing and drying design concepts for paddy rice processing, employing the Analytical Hierarchy Process as a robust decision-making tool. Through a systematic assessment of technical and non-technical criteria and attributes, valuable insights have been gained into the feasibility and desirability of different design concepts.

The methodology facilitated a structured pairwise comparison of design concepts, enabling us to derive priority scores that reflect the relative importance and suitability for real-world implementation of the identified concept. Our findings indicate that Design Concept 2, which focuses on a system that combines the functions of threshing and drying into a single mobile unit, uses diesel powered engine for mechanical power generation for the threshing subsystem and armature that converts mechanical energy to electrical energy to run the electric motors with LPG dual drying unit was selected. It excelled in the overall assessment with the highest weighted score of 0.35. Concept 1, Concept 3 and Concept 4 had weighted scores of 0.28, 0.20 and 0.17, respectively. During the evaluation process of the four (4) identified alternative concepts, seventeen (17) attributes under five criteria (5) were observed. The study underscores the importance of employing holistic evaluation methods for concept selection in agricultural engineering machinery design. Integrating threshing and drying stages is crucial for optimizing paddy rice processing, and our research provides a valuable framework for decision-makers to make informed choices that align with both technical excellence and broader sustainability goals.

It is recommended that the selected concept be further developed and fabricated for evaluation and optimization. As the world transitions towards more resource-efficient and sustainable agricultural practices, integrating innovative design concepts is pivotal for evaluating and selecting the best and appropriate design concept for developing an integrated threshing and drying system. We are optimistic that our work will serve as an example, not only in the realm of paddy rice processing but also as proof of the effectiveness of the Analytical Hierarchy Process in guiding complex design decisions.

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