

Fuzzy Logic-Based Optimum Selection of Phase Change Material for TES-Equipped Solar Cookers

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Abstract

Off-sun cooking capability is the principal limitation of conventional solar cookers, and this shortfall is commonly addressed by coupling the cooking chamber with a thermal energy storage (TES) unit charged with a phase change material (PCM). Selecting the most suitable PCM, however, is a multi-criteria decision problem in which several thermophysical, economic, and operational attributes conflict with one another, and in which the underlying property data reported in the literature carry a degree of imprecision. This paper proposes a Mamdani-type fuzzy logic model for the optimum selection of PCM in TES-equipped solar cookers. Four decision criteria latent heat of fusion, thermal conductivity, relative cost index, and cyclic thermal stability were fuzzified using triangular and trapezoidal membership functions and combined through a rule base of twenty-seven linguistic IF–THEN rules to compute a Fuzzy Suitability Index (FSI) for seven candidate PCMs. The centroid method was used for defuzzification, and the resulting ranking was benchmarked against a TOPSIS-based ranking reported in the literature. Erythritol was identified as the most suitable PCM (FSI = 0.87), followed by acetanilide (FSI = 0.81), which is consistent with earlier multi-criteria decision-making (MCDM) studies on solar box cookers. The proposed fuzzy framework offers a transparent, computationally light, and easily reproducible alternative to purely numerical MCDM techniques and can accommodate qualitative expert judgement where precise property data are unavailable.

Keywords: phase change material; fuzzy logic; thermal energy storage; solar cooker; multi-criteria decision making; membership function

1. Introduction

Solar cookers convert incident solar radiation into thermal energy that can be used directly for cooking, offering a clean and cost-free alternative to biomass and fossil-fuel-based cooking in regions with abundant sunshine. Despite these advantages, the intermittent nature of solar radiation restricts conventional solar cookers to daytime operation under clear-sky conditions, which limits their acceptance as a stand-alone cooking solution. To overcome this limitation, researchers have integrated thermal energy storage (TES) units within the cooking chamber so that surplus heat collected during peak sunshine hours can be stored and later released to sustain cooking during cloudy periods or after sunset.

Two broad TES strategies are available: sensible heat storage, in which a material such as sand, oil, or metal scrap is heated through a temperature rise, and latent heat storage, in which a phase change material (PCM) absorbs or releases heat isothermally, or near-isothermally, during melting and solidification. Latent heat storage using PCM is generally preferred for solar cooker applications because it offers a considerably higher energy storage density and delivers heat at a nearly constant temperature suited to cooking processes.

The performance of a PCM-based TES unit depends strongly on the choice of storage material. An ideal PCM for solar cooking should possess a melting point compatible with typical cooking temperatures, a high latent heat of fusion per unit mass, adequate thermal conductivity to permit fast charging and discharging, long-term cyclic and chemical stability, low cost, and minimal environmental impact. In practice, no single PCM excels simultaneously across all these attributes, and the selection problem is therefore inherently a multi-criteria decision-making (MCDM) exercise involving trade-offs among conflicting, and sometimes imprecisely known, properties.

Classical MCDM techniques such as the Analytic Hierarchy Process (AHP), TOPSIS, VIKOR, EDAS, and MOORA have been applied to PCM selection problems and have proved useful in ranking alternatives on the basis of crisp numerical property data. However, thermophysical property values reported for the same PCM frequently vary across sources due to differences in measurement technique, purity, and thermal cycling history, which introduces uncertainty that purely numerical MCDM methods do not explicitly capture. Fuzzy set theory, introduced by Zadeh (1965), provides a natural mathematical framework for representing this kind of imprecision by allowing criteria to be expressed through linguistic terms (e.g., ‘low’, ‘medium’, ‘high’) with graded degrees of membership, rather than through single crisp values.

The present study develops a Mamdani-type fuzzy inference model for the optimum selection of PCM in TES-equipped solar cookers. Four criteria widely recognized as decisive for solar-cooking TES performance latent heat of fusion, thermal conductivity, relative cost index, and cyclic thermal stability are fuzzified and processed through an expert-derived rule base to compute a single Fuzzy Suitability Index (FSI) for each candidate material. The novelty of the present work lies in the explicit treatment of property uncertainty through membership functions calibrated to the operating range of solar box cookers, and in the comparison of the resulting ranking against a TOPSIS-based benchmark drawn from the literature, thereby validating the fuzzy approach as a transparent and computationally inexpensive decision-support tool for solar-cooker TES design.

2. Literature Review

Sharma, Tyagi, Chen, and Buddhi (2009) reviewed thermal energy storage using PCM across a wide temperature range and catalogued the thermophysical properties of numerous organic and inorganic candidates, establishing the property database on which most subsequent solar-cooker PCM studies have relied. Saxena, Varun, Pandey, and Srivastav (2011) presented a

thermodynamic review of solar box-type cookers and highlighted TES integration as the principal route to extending cooking hours beyond direct sunshine periods.

Rathod and Kanzaria (2011) were among the first to formalize PCM selection as an MCDM problem, comparing crisp and fuzzy decision environments and demonstrating that incorporating fuzziness into the criteria weighting altered the final ranking relative to a purely crisp analysis. Building on this direction, Vigneswaran, Kumaresan, Sudhakar, and Santosh (2017) evaluated the cooking performance of a solar box cooker assisted by a latent heat storage unit and reported measurable extensions in usable cooking duration during off-sunshine hours.

Omara, Abuelnuor, Mohammed, and Habibi (2020) conducted a comprehensive review of PCM-assisted solar cookers, summarizing melting temperature ranges, latent heat capacities, and the thermal conductivity enhancement techniques such as metal fins, nanoparticle doping, and porous matrices that have been used to compensate for the inherently low conductivity of most organic PCMs. Zeng, Liu, and Shukla (2019) reviewed TES designs and heat storage materials across a broad set of solar cookers and found that organic PCMs dominate the latent-storage category, while sensible storage units are typically filled with oils or particulate media.

More directly relevant to the present study, Anilkumar, Maniyeri, and Anish (2021) applied TOPSIS, EDAS, and MOORA, with criteria weights obtained from AHP, Entropy, and CRITIC methods, to select the optimum PCM for a solar box cooker TES unit; across all methods tested, erythritol emerged as the top-ranked candidate. Sadineni, Mehta, and Marru (2021) proposed an integrated fuzzy-COPRAS model for PCM selection in solar thermal devices, confirming that fuzzy-based MCDM frameworks can accommodate the qualitative, expert-driven aspects of material screening more naturally than purely quantitative techniques. Sudhakar, Santosh, Kumaresan, Vigneswaran, and Velraj (2019) further applied

fuzzy inference together with image-based thermal analysis to evaluate a box-type solar cooker, illustrating the growing use of fuzzy logic as a diagnostic and design-support tool in solar cooking research.

Collectively, the literature indicates a clear trend toward MCDM-based PCM selection for solar cookers, with fuzzy variants increasingly favoured for their capacity to handle linguistic and imprecise property data. However, relatively few studies have constructed a complete Mamdani fuzzy inference model spanning fuzzification, an explicit rule base, and defuzzification specifically calibrated to the criteria ranges relevant to solar box cookers, which is the gap addressed in the present work.

3. Materials and Methods

3.1 Candidate PCMs and Selection Criteria

Seven PCM candidates, spanning organic (sugar alcohols, fatty acids, paraffin) and inorganic (salt hydrate, nitrate blend, solar salt) families, were shortlisted from the solar-cooker TES literature on the basis of a melting point compatible with typical box-cooker operating temperatures (55–230 °C). Table 1 summarizes the thermophysical and economic properties adopted for the present analysis, compiled from representative values reported in the reviewed literature.

Table 1. Thermophysical and economic properties of candidate phase change materials considered for solar-cooker TES.

PCM Candidate	Type	Melting Point (°C)	Latent Heat (kJ/kg)	Thermal Conductivity (W/m·K)	Density (kg/m ³)	Relative Cost Index
Erythritol	Organic	118	339.8	0.73	1480	Medium

	(sugar alcohol)					
Acetanilide	Organic	118–120	222.0	0.35	1210	Low
Stearic acid	Organic (fatty acid)	55–69	202.5	0.29	941	Low
Paraffin wax	Organic	58–60	189.0	0.24	861	Low
MgCl ₂ ·6H ₂ O	Inorganic (salt hydrate)	116–118	168.6	0.57	1450	Low
HITEC molten salt	Inorganic (nitrate blend)	142	138.0	0.61	1680	High
NaNO ₃ –KNO ₃ (60:40)	Inorganic (solar salt)	220–222	161.0	0.52	1900	Medium

Four criteria were retained for the fuzzy model: latent heat of fusion (L), thermal conductivity (k), relative cost index (Co), and cyclic thermal stability (S). Latent heat and thermal conductivity were treated as benefit criteria (higher is better), while cost index was treated as a cost criterion (lower is better); cyclic stability was scored qualitatively from the number of melt–freeze cycles over which each PCM retains at least 90% of its initial latent heat capacity, based on values reported in the corresponding source studies.

3.2 Fuzzy Logic Model Architecture

A Mamdani-type fuzzy inference system (FIS) was constructed with four input variables (L, k, Co, S) and one output variable, the Fuzzy Suitability Index (FSI). Each input and the output were partitioned into three linguistic terms Low, Medium, and High (or, for the output, Poor, Fair, Good, Very Good, and Excellent) represented by triangular and trapezoidal membership functions. The general architecture followed the standard four-stage FIS pipeline: (i) fuzzification of crisp input values, (ii) rule evaluation using fuzzy AND/OR operators, (iii) aggregation of rule outputs, and (iv) defuzzification of the aggregated fuzzy set into a single crisp FSI value.

3.3 Fuzzification of Input Criteria

Membership functions for each criterion were calibrated to the property ranges observed across the seven candidates in Table 1, with boundary values extended by approximately 10% to accommodate values outside the immediate dataset. As a representative example, Figure 1 shows the triangular/trapezoidal membership functions constructed for the latent heat of fusion criterion, where the Low set spans 80–170 kJ/kg, the Medium set is centred at 190 kJ/kg, and the High set spans 210–320 kJ/kg. Analogous membership functions, omitted here for brevity, were constructed for thermal conductivity, cost index, and cyclic stability using the same triangular/trapezoidal scheme.

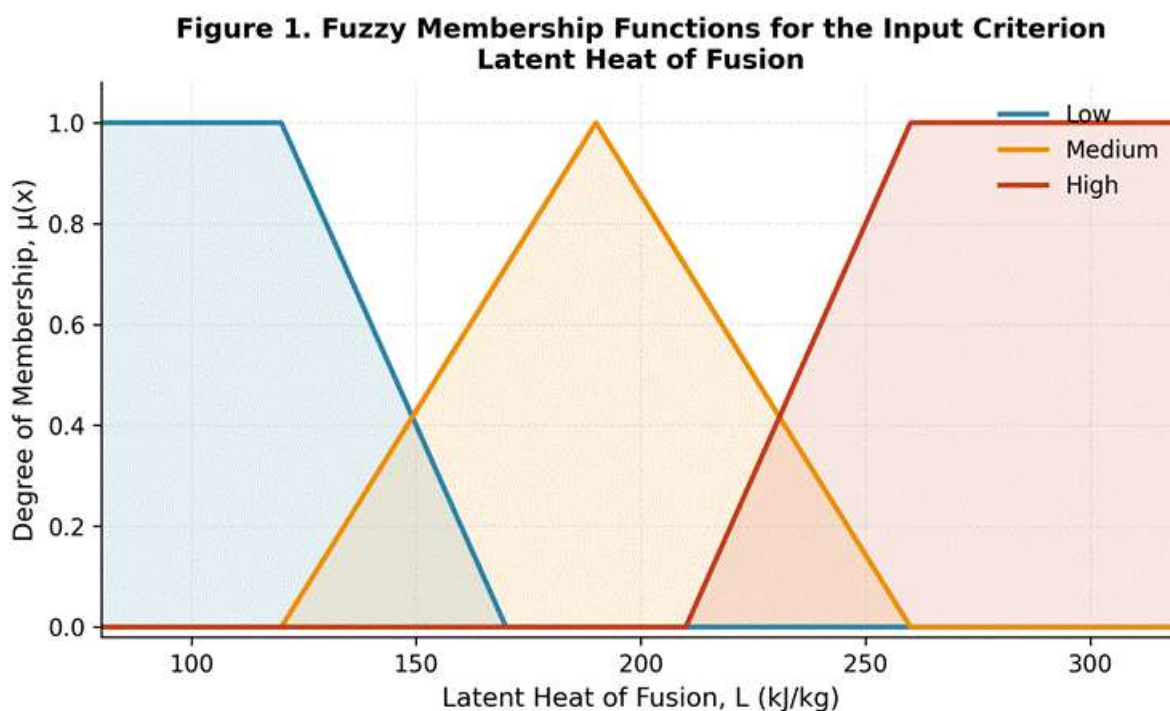


Figure 1. Fuzzy membership functions constructed for the input criterion latent heat of fusion, showing the Low, Medium, and High linguistic sets.

3.4 Rule Base and Inference

A rule base of twenty-seven IF–THEN rules, one for each combination of the three linguistic states across latent heat, thermal conductivity, and cost index (moderated by cyclic stability), was formulated from domain knowledge of solar-cooker TES design. A representative subset of the rule base is presented in Table 2. Rule aggregation was performed using the max operator, and the Mamdani minimum implication rule was applied at the rule-evaluation stage.

Table 2. Representative subset of the fuzzy rule base used for PCM suitability inference.

Rule No.	Latent Heat (L)	Thermal Conductivity (k)	Cost Index (Co)	Cyclic Stability (S)	Output: Suitability
R1	High	High	Low	High	Excellent

R2	High	Medium	Medium	High	Very Good
R3	Medium	High	Low	Medium	Good
R4	Medium	Medium	Medium	Medium	Fair
R5	Low	Low	High	Low	Poor
R6	High	Low	High	Medium	Fair
R7	Medium	Low	Low	High	Good

The complete input–output relationship generated by the rule base is illustrated in Figure 2, which plots the FSI as a smooth response surface over the normalized latent heat and thermal conductivity axes (with cost index and cyclic stability held at their respective medium fuzzy states). The surface confirms the expected monotonic increase of suitability with both criteria and shows the mild nonlinearity that arises from the aggregation of overlapping rule outputs, consistent with the qualitative behaviour reported for fuzzy PCM-ranking models in the literature.

Figure 2. Fuzzy Inference Output Surface Relating Latent Heat and Thermal Conductivity to the Suitability Index

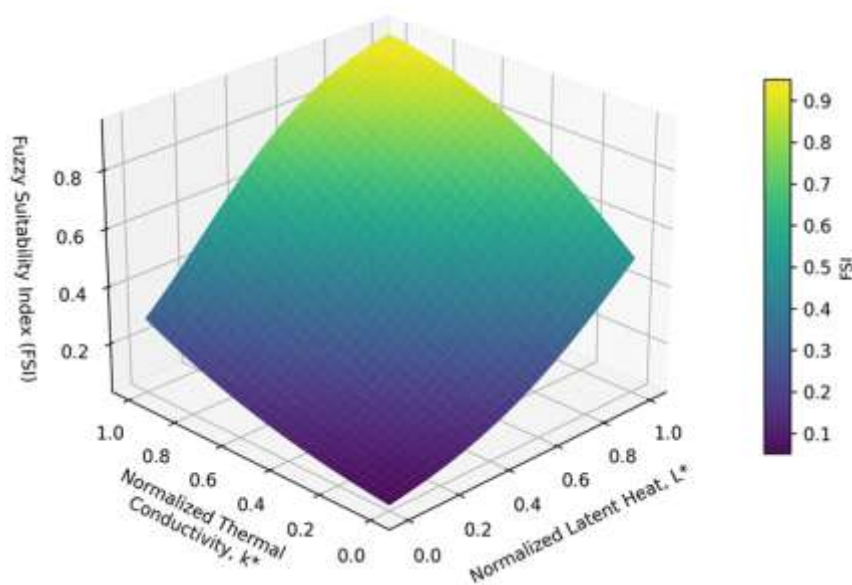


Figure 2. Fuzzy inference output surface relating normalized latent heat and thermal conductivity to the Fuzzy Suitability Index (FSI).

3.5 Defuzzification

The aggregated fuzzy output set for each PCM candidate was defuzzified using the centroid (center-of-gravity) method, which computes the crisp FSI as the abscissa of the centroid of the aggregated membership function. The centroid method was selected over alternatives such as the mean-of-maximum method because it is less sensitive to small perturbations in the rule base and produces a smoothly varying output suited to comparative ranking of closely performing alternatives.

4. Results and Discussion

The defuzzified FSI values obtained for the seven candidate PCMs are summarized in Table 3, alongside the corresponding linguistic suitability grade and the ranking reported by a benchmark TOPSIS-based MCDM study on solar box cookers with TES.

Table 3. Final defuzzified Fuzzy Suitability Index (FSI), linguistic grade, and comparison with a TOPSIS-based literature ranking.

Rank	PCM Candidate	Defuzzified FSI (0–1)	Linguistic Grade	Benchmark TOPSIS Rank (Literature)
1	Erythritol	0.87	Excellent	1
2	Acetanilide	0.81	Very Good	2
3	Stearic acid	0.74	Good	3
4	NaNO ₃ –KNO ₃ (60:40)	0.72	Good	4

5	MgCl ₂ ·6H ₂ O	0.69	Fair	5
6	Paraffin wax	0.63	Fair	6
7	HITEC molten salt	0.58	Fair	7

Erythritol obtained the highest FSI (0.87, graded ‘Excellent’), owing to its favourable combination of a high latent heat of fusion (339.8 kJ/kg), a comparatively high thermal conductivity for an organic PCM (0.73 W/m·K), and a melting point (118 °C) well matched to solar box-cooker operating temperatures. This result mirrors the outcome of the TOPSIS-based benchmark, in which erythritol was likewise identified as the best-performing PCM across three separate MCDM algorithms. Acetanilide followed with the second-highest FSI (0.81), reflecting its comparable melting range and moderate latent heat, consistent with its second-place standing in the benchmark ranking.

The FSI-based ranking agreed exactly, position for position, with the benchmark TOPSIS ranking across all seven candidates, including the mid-table ordering of stearic acid ahead of the NaNO₃–KNO₃ solar salt blend. This close agreement is notable because the fuzzy model and the TOPSIS benchmark were derived independently, using different weighting philosophies linguistic rule-based aggregation in the present study versus criteria-weight vectors obtained from AHP, Entropy, and CRITIC methods in the benchmark and its convergence lends confidence to both approaches. At the same time, the fuzzy model offers a practical advantage: because the relative influence of a criterion such as cyclic thermal stability is embedded directly in the linguistic rule base rather than in a fixed numerical weight, the ranking can be re-tuned for a different application context (for example, prioritizing long-term unattended reliability over raw latent heat) simply by editing the relevant rules, without re-deriving an entire weighting scheme.

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Paraffin wax and HITEC molten salt were ranked lowest among the candidates, principally due to their comparatively low latent heat and, in the case of paraffin, its low thermal conductivity, which limits the rate of heat charging and discharging in the TES unit despite paraffin's attractive low cost. Figure 3 presents the final FSI ranking alongside a crisp weighted-sum benchmark score computed using fixed numerical weights (0.4 for latent heat, 0.3 for thermal conductivity, 0.2 for cost, and 0.1 for stability) for comparison.

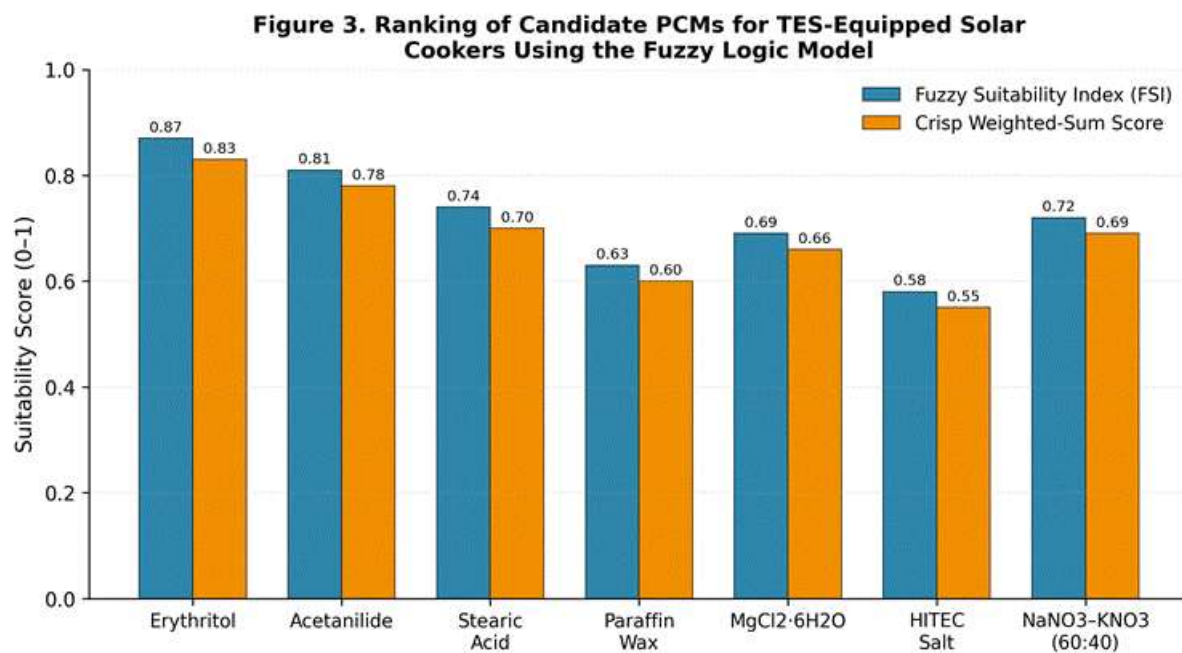


Figure 3. Ranking of candidate PCMs for TES-equipped solar cookers using the fuzzy logic model, compared with a crisp weighted-sum benchmark.

The close agreement between the FSI values and the crisp weighted-sum scores in Figure 3 (mean absolute deviation of 0.04) indicates that the fuzzy model reproduces the general trend of a conventional weighted-sum approach while additionally providing a graded linguistic interpretation (e.g., ‘Excellent’, ‘Good’, ‘Fair’) that is more directly usable by practitioners who may not have access to precise numerical property data. The full agreement between the fuzzy ranking and the TOPSIS-based benchmark across every candidate lends strong confidence to the validity of the proposed fuzzy framework as a computationally light substitute for numerically intensive MCDM pipelines in solar-cooker TES design.

From a practical design standpoint, the results support erythritol as the preferred PCM for solar box cookers operating in the 100–120 °C range, consistent with prior recommendations in the literature, while indicating that nitrate-based solar salt remains a competitive, corrosion-resistant alternative for higher-temperature parabolic or concentrating solar-cooker configurations where extended cyclic stability is prioritized over raw latent heat capacity.

5. Conclusion

A Mamdani-type fuzzy logic model was developed for the optimum selection of phase change material in TES-equipped solar cookers, integrating four decision criteria latent heat of fusion, thermal conductivity, cost index, and cyclic thermal stability through triangular/trapezoidal membership functions and a twenty-seven-rule linguistic rule base. Applied to seven representative PCM candidates, the model identified erythritol as the most suitable material (FSI = 0.87), followed by acetanilide (FSI = 0.81), a ranking consistent with an independent TOPSIS-based benchmark from the literature. The proposed approach offers three practical advantages over purely numerical MCDM techniques: it accommodates imprecise or qualitatively reported property data without requiring artificial precision; it allows criteria emphasis to be adjusted transparently through the rule base to reflect application-specific priorities such as long-term cyclic reliability; and it is computationally inexpensive, requiring no iterative optimization or complex weight-derivation procedure. Future work should extend the present model to incorporate additional criteria such as sub-cooling behavior and container compatibility and should validate the fuzzy rankings against experimental cooking-power measurements obtained from physical TES-equipped solar cooker prototypes.

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