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Comprehensive Performance Evaluation of Phase Change Materials Using Multi-Attribute Decision Making Method: TOPSIS

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Abstract- Phase change materials store large amount of heat in the form of latent heat of fusion. For latent heat thermal energy storage systems, the comprehensive performance evaluation of phase change materials is very important task for the selection of the most suitable phase change material from among multiple alternative one. It is a typical multi-attribute decision making (MADM) problem. This work proposed a MADM approach to evaluate the comprehensive performance of the phase change materials using technique for order preference by similarity to ideal solution (TOPSIS), and applied it to evaluate the comprehensive performance of 9 alternative phase change materials for solar domestic hot water system. As the result, the comprehensive performance ranking of the phase change materials was n-eicosane, n-octadecane, n-nonadecane, RT 60, RT 30, calcium chloride hexa-hydrate, n-docosane, p116, and stearic acid. It could be actively applied to not only the phase change materials but also various materials comprehensive performance evaluation ones arising in practice.

Keywords: Phase Change Material, Multi-Attribute Decision Making, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Solar Domestic Hot Water System.

I. Introduction

Phase change material (PCM) has a capacity to store large amount of heat in the form of latent heat of fusion. When a material melts or solidifies, it absorbs or releases the latent heat. If the melting point of the materials lies within the working temperature, it has an extra heat storing capacity. The latent heat thermal energy storage system (LHTESS) requires an appropriate PCM for the thermal energy storage application. The PCMs used in low temperature applications are classified as paraffin, fatty acids and salt hydrates [1]. The ideal PCM should have high sensitive heat capacity and fusion heat, high density, high thermal conductivity, chemically inert, non-toxic, non-flammable, non-hazardous, and inexpensive. Therefore, the selection of the suitable PCM plays very important role tor the LHTESS.

There are many PCMs applicable to LHTESS. Many works selected the PCM based on their practical experience and availability for the given applications. To scientifically evaluate the comprehensive performance of the PCM and select the best one, the multiple performance attributes should be considered, simultaneously. Therefore, the comprehensive performance evaluation of the PCMs and PCM selection problem becomes multi-attribute decision making (MADM) problem that has to evaluate the comprehensive performances of the alternative PCMs and rank them in consideration of their multiple conflicting attributes. It could be solved by applying the MADM methods such as analytic hierarchy process (AHP), simple additive weighting (SAW) method, technique for order preference by similarity to ideal solution (TOPSIS) method, grey relational analysis (GRA), VIse Kriterijumska Optimizacija Kompromisno Resenje (VIKOR) method, preference ranking organization method for enrichment evaluations (PROMETHEE), rank sum ratio (RSR) method, etc [2,3].

Many research works applied the MADMs to solve the PCM selection problems. Rathod et al.[1] selected the best PCM from among 9 alternative PCMs (calcium chloride hexa-hydrate, stearic acid, p116, RT 60, parafn wax RT 30, n-docosane, n-octadecane, n-nonadecane and n-eicosane) in consideration of 6 attributes (latent heat, density, specific heats for solid and liquid, thermal conductivity and cost) using TOPSIS and fuzzy TOPSIS methods under the crisp and fuzzy environment. Zakeri1 et al.[4] selected the best PCM from among above-mentioned 9 alternative PCMs in consideration of above-mentioned 6 attributes using simple ranking process (SRP) method, and then compared the result with the results obtained from 3 well-known MADMs: TOPSIS, WPM, and VIKOR. Rastogi et al.[5] selected the assessed the performance of 35 alternative PCMs for heating, ventilation and air-conditioning applications in consideration of 5 attributes (phase change temperature, density, fusion heat, specific heat and thermal conductivity) using TOPSIS. Bhowmik et al.[6] selected the best PCM for energy storage from 5 alternative PCMs (magnesium, aluminium, , zinc, , 88Al:12Si and 60Al:34Mg:6Zn) in consideration of 4 attributes (latent heat, melting point, density and total energy stored) using multi-objective optimization on the basis of ratio analysis (MOORA) plus full multiplicative form (MULTIMOORA) and multi-objective optimization on the basis of simple ratio analysis (MOOSRA). Yang et al.[7] selected the best PCM from among 8 alternative PCMs (Paraffins $C_{31}H_{64}$, $C_{32}H_{66}$, $C_{33}H_{68}$, $C_{34}H_{70}$, stearic acid $CH_3(CH_2)_{16}\cdot COOH$, salt hydrate $Ba(OH)_2\cdot 8H_2O$, Eutectic $LiNO_3$ (14%)-$MgNO_3\cdot 6H_2O$ (86%), Urea (82%) +$LiNO_3$ (18%)) for the ground source heat pump integrated with phase change thermal storage system in consideration of 7 qualitative indices (volume change, vapour pressure, super cooling, phase separation, recycle, toxicity and flammability) and 5 quantitative indices

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(latent heat, thermal conductivity, density, specific heat and cost) using TOPSIS. Maghsoodi et al.[8] selected the best PCM from among 14 alternative PCMs in consideration of melting temperature, latent heat storage capacity, thermal conductivity, specific heat capacity, energy density, unit price, and maintenance and operational costs, technological complexity, and risk level using the interval-valued target-based BWM-CoCoMULTIMOORA method combined with the best-worst method (BWM), combined compromise solution (CoCoSo) and multi-objective optimization of ratio analysis plus the full multiplicative form (MULTIMOORA). Gadhave et al.[9] selected the PCM for domestic water heating using 3 MADMs: VIKOR, TOPSIS, and EXPROM2. Oluah et al.[10] selected the PCM for improved performance of Trombe wall systems using TOPSIS. Akgün et al.[11] selected the carbon-based nanomaterials in the PCMs using combined MADM.

This work evaluated the comprehensive performance of the PCMs using TOPSIS, which is one of the most well-known and widely-used popular MADMs.

Section 2 described a comprehensive performance evaluation approach of the PCMs using TOPSIS. Section 3 applied it to the PCM performance evaluation for solar domestic hot water system.

II. Methodology

Comprehensive performance index of the PCM using TOPSIS

This subsection shows the details to calculate the comprehensive performance indices (CPIs) of the PCMs using TOPSIS [2,3,12].

Let y_{ik} be the value of k-th performance attribute of ***i-th*** alternative PCM. (i= 1, 2, …, n, k= 1, 2, …, L) All the values constitute the decision matrix (DM) $Y=(y_{ik})_{n\times L}$, where n is the number of the alternative PCMs ($n\geq 2$) and L is the number of the performance attributes ($L\geq 2$).

The main steps to calculate the TOPSIS-based CPIs of the PCMs are as follows:

(1) Constitute the normalized DM $Z=(z_{ik})_{n\times L}$ by normalizing the DM $Y=(y_{ik})_{n\times L}$.

This work uses linear min-max normalization formula:

$$z_{ik}=\begin{cases}(y_{ik}-y_{k\min})/(y_{k\max}-y_{k\min});k\in K^{+}\\(y_{k\max}-y_{ik})/(y_{k\max}-y_{k\min});k\in K^{-}\end{cases}, \quad (1)$$

where K^+ and K^- are the index sets of the benefit and cost attributes, and $y_{k\max}$ and $y_{k\min}$ are the maximum and minimum values of the k-*th* attribute, respectively.

The normalized value enables to understand the status of each attribute. The value 1 represents that the attribute status is the best, the value 0.5 the intermediate, and the value 0 the worst.

(2) Constitute the weighted normalized DM $U=(u_{ik})_{n\times L}$:

$$u_{ik}=w_k\times z_{ik}. \quad (2)$$

where w_k is the weight of the k-*th* performance attribute ($w_1+...+w_k+...+w_L=1$).

The attribute weights could be determined using AHP [13].

(3) Select the positive and negative ideal solutions $\boldsymbol{PI}=(PI_1,\dots,PI_k,\dots,PI_L)$ and $\boldsymbol{NI}=(NI_1,\dots,NI_k,\dots,NI_L)$ as follows:

$$PI_k=\max_{1\le i\le n}u_{ik},\ NI_k=\min_{1\le i\le n}u_{ik};\ k=1,2,...,L. \quad (3)$$

$$PI_k=\max_{1\le i\le n}u_{ik}=\max_{1\le i\le n}w_k\cdot z_{ik}=w_k\cdot\max_{1\le i\le n}z_{ik}=w_k\cdot 1=w_k$$

and

$$NI_k=\min_{1\le i\le n}u_{ik}=w_k\cdot\min_{1\le i\le n}z_{ik}=0.$$

(4) Calculate the Euclidean distances of the alternative PCMs to the positive and negative ideal solutions ***PI*** and ***NI***: (i= 1, 2,..., n)

$$D_i^{+}=\sqrt{\sum_{k=1}^{L}(PI_k-u_{ik})^2}=\sqrt{\sum_{k=1}^{L}w_k^2(1-z_{ik})^2}, \quad (4)$$

$$D_i^{-}=\sqrt{\sum_{k=1}^{L}(NI_k-u_{ik})^2}=\sqrt{\sum_{k=1}^{L}w_k^2z_{ik}^2}. \quad (5)$$

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(5) Calculate the relative closeness values of the alternative PCMs:

$$T_i = D_i^- \Big/ (D_i^+ + D_i^-)\ ;\ i = 1, 2, ..., n. \quad (6)$$

It is called TOPSIS-based CPI.

The CPI value belongs to [0, 1]. The higher the CPI value is, the better the PCM is.

The authors developed the MATLAB program for employing the proposed method.

Sensitive analysis method on attribute weight for TOPSIS-based CPI

This subsection proposed a sensitivity analysis method on attribute weight for the TOPSIS-based CPI.

Derive the partial derivative of the TOPSIS-based CPI C_i with respect to k-th attribute weight w_k.

Since $C_i = D_i^- \Big/ (D_i^+ + D_i^-)$, $D_i^+ = \sqrt{\sum_{k=1}^{L} w_k^2 (1 - z_{ik})^2}$ and $D_i^- = \sqrt{\sum_{k=1}^{L} w_k^2 z_{ik}^2}$, we have

$$\frac{\partial C_i}{\partial w_k} = \frac{\partial C_i}{\partial D_i^+} \cdot \frac{\partial D_i^+}{\partial w_k} + \frac{\partial C_i}{\partial D_i^-} \cdot \frac{\partial D_i^-}{\partial w_k}. \quad (7)$$

In this equation,

$$\frac{\partial C_i}{\partial D_i^+} = -\frac{D_i^-}{(D_i^+ + D_i^-)^2}, \quad (8)$$

$$\frac{\partial C_i}{\partial D_i^-} = \frac{1}{D_i^+ + D_i^-} - \frac{D_i^-}{(D_i^+ + D_i^-)^2} = \frac{D_i^+}{(D_i^+ + D_i^-)^2}, \quad (9)$$

$$\frac{\partial D_i^+}{\partial w_k} = \frac{1}{2\sqrt{\sum_{j=1}^{p} w_j^2 (1 - z_{ij})^2}} \cdot \frac{\partial}{\partial w_k}\left[\sum_{j=1}^{p} w_j^2 (1 - z_{ij})^2\right]$$

$$= \frac{1}{2\sqrt{\sum_{j=1}^{p} w_j^2 (1 - z_{ij})^2}} \cdot 2 w_k (1 - z_{ik})^2 = \frac{w_k (1 - z_{ik})^2}{\sqrt{\sum_{j=1}^{p} w_j^2 (1 - z_{ij})^2}}, \quad (10)$$

$$\frac{\partial D_i^-}{\partial w_k} = \frac{1}{2\sqrt{\sum_{j=1}^{p} w_j^2 z_{ij}^2}} \cdot \frac{\partial}{\partial w_k}\left[\sum_{j=1}^{p} w_j^2 z_{ij}^2\right] = \frac{1}{2\sqrt{\sum_{j=1}^{p} w_j^2 z_{ij}^2}} \cdot 2 w_k z_{ik}^2 = \frac{w_k z_{ik}^2}{\sqrt{\sum_{j=1}^{p} w_j^2 z_{ij}^2}}. \quad (11)$$

Therefore,

$$\frac{\partial C_i}{\partial w_k} = \frac{\partial C_i}{\partial D_i^+} \cdot \frac{\partial D_i^+}{\partial w_k} + \frac{\partial C_i}{\partial D_i^-} \cdot \frac{\partial D_i^-}{\partial w_k}$$

$$= -\frac{D_i^-}{(D_i^+ + D_i^-)^2} \cdot \frac{w_k (1 - z_{ik})^2}{\sqrt{\sum_{j=1}^{p} w_j^2 (1 - z_{ij})^2}} + \frac{D_i^+}{(D_i^+ + D_i^-)^2} \cdot \frac{w_k z_{ik}^2}{\sqrt{\sum_{j=1}^{p} w_j^2 z_{ij}^2}}$$

$$= \frac{w_k}{(D_i^+ + D_i^-)^2} \cdot \left[\frac{z_{ik}^2 D_i^+}{\sqrt{\sum_{j=1}^{p} w_j^2 z_{ij}^2}} - \frac{(1 - z_{ik})^2 D_i^-}{\sqrt{\sum_{j=1}^{p} w_j^2 (1 - z_{ij})^2}}\right] = \frac{w_k}{(D_i^+ + D_i^-)^2} \cdot \left[\frac{z_{ik}^2 D_i^+}{D_i^-} - \frac{(1 - z_{ik})^2 D_i^-}{D_i^+}\right].$$

Conclusively,

$$\frac{\partial C_i}{\partial w_k} = \frac{w_k}{\left(D_i^+ + D_i^-\right)^2} \cdot \left[\frac{z_{ik}^2 (D_i^+)^2 - (1 - z_{ik})^2 (D_i^-)^2}{D_i^- \cdot D_i^+}\right]. \quad (12)$$

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The value of $s_{ik} = \dfrac{\partial C_i}{\partial w_k}$ shows the sensitivity degree on *k*-th attribute weight for the TOPSIS-based CPI C_i.

In case of $s_{ik} > 0$, when *k*-th attribute weight increases (decreases), the CPI of *i*-th alternative also increases (decreases). In case of $s_{ik} < 0$, when *k*-th attribute weight increases (decreases), the CPI of *i*-th alternative decreases (increases). The absolute value of s_{ik} reflects the velocity of increase/decrease of the CPI of *i*-th alternative according to the change of *k*-th attribute weight, namely, the impact of *k*-th attribute weight on the CPI of *i*-th alternative. The value of $S_k = \frac{1}{n}\sum_{i=1}^{n}|s_{ik}|$ shows the overall sensitivity degree to *k*-th attribute weight on the CPIs of all the alternatives. The larger the value of S_k is, the higher the impact of *k*-th attribute weight is.

III. Results and discussion

This work applied the proposed approach to the comprehensive performance evaluation and ranking of the PCMs for solar domestic hot water system.

The PCMs used in the solar domestic hot water system should have the melting point 30–60 ºC. This work selected nine PCMs such as calcium chloride hexa-hydrate (A1), stearic acid (A2), p116 (A3), RT 60 (A4), parafn wax RT 30 (A5), n-docosane (A6), n-octadecane (a7), n-nonadecane (A8) and n-eicosane (A9) as the alternative PCMs, and selected five attributes such as the latent heat (LH), density (D), specific heat for solid (SHs), specific heat for liquid (SHl), and thermal conductivity (TC) as the PCM performance attributes [1,4,13,14]. Table 1 shows the performance attribute values of the alternative PCMs for solar domestic hot water system.

Table 1: Performance attribute values of the alternative PCMs.

PCMs	LH, J/kg	D, kg/m^3	SHs, kJ/kg K	SHl, kJ/kg K	TC, W/m K
A1	169.98	1560	1.46	2.13	1.09
A2	186.5	903	2.83	2.38	0.18
A3	190	830	2.1	2.1	0.21
A4	214.4	850	0.9	0.9	0.2
A5	206	789	1.8	2.4	0.18
A6	194.6	785	1.93	2.38	0.22
A7	245	773.22	0.3767	2.267	0.14
A8	222	775.8	1.7189	1.921	0.142
A9	247	776.33	0.7467	2.377	0.138

To evaluate the comprehensive performance of 9 alternative PCMs, this work applied well-known popular MADM: TOPSIS.

To determine the performance attribute weights, this work used the AHP with the simplest questionnaire [16]. Table 2 shows the simplest questionnaire for PCM performance attribute weighting.

Table 2. Simplest questionnaire for PCM performance attribute weighting.

	LH	D	SHs	SHl	TC
LH	1	5	7	7	5
D		1	5	5	2
SHs			1	1	5
SHl				1	5
TC					1

We constituted the pairwise comparison matrix from the completed questionnaire Table 2.

From Table 2, its upper triangular matrix is as follows:

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$$\begin{pmatrix} 1 & 5 & 7 & 7 & 5 \\ & 1 & 5 & 5 & 1/2 \\ & & 1 & 1 & 1/5 \\ & & & 1 & 1/5 \\ & & & & 1 \end{pmatrix}.$$

Since the elements of the lower triangular matrix are the positive reciprocal of the elements of the upper triangular matrix, the completed pairwise comparison matrix is as follows:

$$A = \begin{pmatrix} 1 & 5 & 7 & 7 & 5 \\ 1/5 & 1 & 5 & 5 & 1/2 \\ 1/7 & 1/5 & 1 & 1 & 1/5 \\ 1/7 & 1/5 & 1 & 1 & 1/5 \\ 1/5 & 2 & 5 & 5 & 1 \end{pmatrix}.$$

Evaluate the consistency of the pairwise comparison matrix using the consistency ratio *CR*.

λ_{max}= 5.326186, *CI*= 0.081546, *RI* =1.12, *CR*= 0.072809.

As *CR*= 0.072809< 0.1, the pairwise comparison matrix *A* satisfied the consistency.

The performance attribute weights calculated using eigenvector method are as follows:

w_1= 0.555492, w_2= 0.153279, w_3= 0.045155, w_4= 0.045155, w_5= 0.200918.

We constituted the normalized DM using the linear min-max normalization formula Eq. (1). Table 3 shows the normalized DM.

Table 3. Normalized DM.

PCMs	LH	D	SHs	SHl	TC
A1	0.000	1.000	0.442	0.820	1.000
A2	0.214	0.165	1.000	0.987	0.044
A3	0.260	0.072	0.702	0.800	0.076
A4	0.577	0.098	0.213	0.000	0.065
A5	0.468	0.020	0.580	1.000	0.044
A6	0.320	0.015	0.633	0.987	0.086
A7	0.974	0.000	0.000	0.911	0.002
A8	0.675	0.003	0.547	0.681	0.004
A9	1.000	0.004	0.151	0.985	0.000

We calculated the CPIs and CPRs of 9 alternative PCMs using TOPSIS. Table 4 shows the CPIs and CPRs of 9 alternative PCMs obtained from the TOPSIS.

Table 4. CPIs and CPRs of 9 alternative PCMs obtained from TOPSIS.

PCMs	CPIs	CPRs
A1	0.315	6
A2	0.218	9
A3	0.245	8
A4	0.489	4
A5	0.409	5
A6	0.294	7
A7	0.679	2

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A8	0.548	3
A9	0.686	1

Fig. 1 shows the bar graph of the CPIs of 9 alternative PCMs obtained from the TOPSIS.

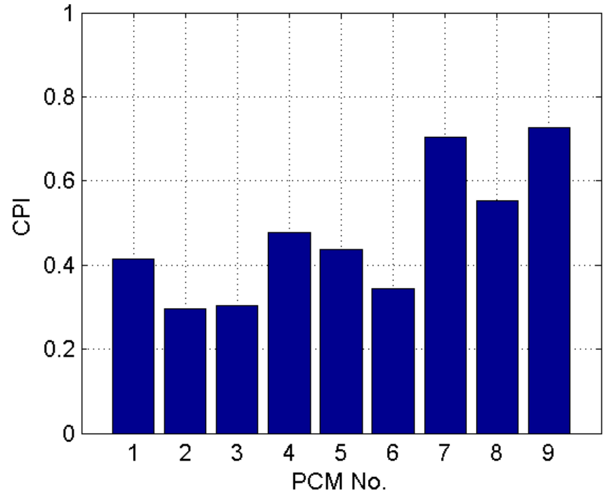

Fig. 1. Bar graph of the CPIs of 9 alternative PCMs.

From the Table 4 and Fig. 1, we can know that the comprehensive performance ranking of 9 alternative PCMs is A9, A7, A8, A4, A5, A1, A6, A3, and A2.

This work considered only five performance attributes such as LH, D, SHs, SHl and TC, and did not include the unit price, maintenance and operational costs of the PCMs as the performance attributes. In practice, we first determine CPRs of the alternative PCMs in consideration of five performance attributes, and then select the best PCM that allows the cost condition.

Table 5 shows the sensitivity degrees on the attribute weights for the TOPSIS-based CPIs of the alternative PCMs. Table 6 shows the overall sensitivity degrees and ranks on the attribute weights for the CPIs.

Table 5. Sensitivity degrees and ranks on attribute weights for TOPSIS-based CPIs of the alternative PCMs

PCMs	Sensitivity degrees					Sensitivity ranks				
	w_1	w_2	w_3	w_4	w_5	w_1	w_2	w_3	w_4	w_5
A1	-0.388	0.504	0.019	0.099	0.661	3	2	5	4	1
A2	-0.010	-0.037	0.406	0.396	-0.125	5	4	1	2	3
A3	0.044	-0.103	0.172	0.226	-0.133	5	4	2	1	3
A4	0.228	-0.272	-0.057	-0.100	-0.386	3	2	5	4	1
A5	0.159	-0.241	0.039	0.155	-0.300	3	2	5	4	1
A6	0.073	-0.154	0.102	0.263	-0.166	5	3	4	1	2
A7	0.389	-0.507	-0.149	0.027	-0.661	3	2	4	5	1
A8	0.291	-0.391	-0.000	0.025	-0.511	3	2	5	4	1
A9	0.385	-0.503	-0.107	0.030	-0.664	3	2	4	5	1

Table 6. Overall sensitivity degrees and ranks on attribute weights for TOPSIS-based CPIs

	w_1	w_2	w_3	w_4	w_5
Overall sensitivity degrees	0.218	0.301	0.117	0.147	0.401
Overall sensitivity ranks	3	2	5	4	1

From Tables 5 and 6, we can know the followings.

The most sensitive attribute weight for the CPIs of the A1, A4, A5, A7, A8 and A9 is w_5. The most sensitive attribute weight for the CPI of the A2 is w_3. The most sensitive attribute weight for the CPIs of the A3 and A6 is w_4. In overall, the most sensitive attribute weight for the CPI of all the alternative PCMs is w_5, and the overall sensitivity ranks on the attribute weights are w_5, w_2, w_1, w_4 and w_3.

For validation confirmation on the ranking results of the PCMs, we applied other four MADMs (SAW, GRA, VIKOR and PROMETHEE) to the given problem. Table 7 shows the CPRs of 9 alternative PCMs obtained from 5 MADMs. The mean correlation coefficient between the CPRs from TOPSIS and other MADMs was 0.921. It demonstrates that the CPRs of 9 alternative PCMs from TOPSIS were valid.

Table 7. CPRs of 9 alternative PCMs obtained from 5 MADMs.

PCMs	TOPSIS	SAW	GRA	VIKOR	PROMETHEE
A1	6	4	3	7	4
A2	9	8	7	9	8
A3	8	9	9	8	9
A4	4	5	6	4	5
A5	5	6	5	5	6
A6	7	7	8	6	7
A7	2	2	2	2	2
A8	3	3	4	3	3
A9	1	1	1	1	1

IV. Conclusions

This work evaluated the comprehensive performance of the PCMs for solar domestic hot water system using TOPSIS.

As the result, the comprehensive performance ranking of the PCMs for solar domestic hot water system was n-eicosane, n-octadecane, n-nonadecane, RT 60, RT 30, calcium chloride hexa-hydrate, n-docosane, p116, and stearic acid.

The approach could be actively applied to not only the PCMs performance evaluation problem but also other various materials evaluation ones in practice. To apply it to the other materials, it needs to select the appropriate performance attributes suited to the given material selection problem, and determine reasonable attribute weights.

The drawback of this work is that we did not consider the influence of the performance attribute weights on the CPIs and CPRs owing to the limited time. Our future work will address this issue.

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CRediT authorship contribution statement

Chol-Ryong Pak: Conceptualization, Investigation, Methodology, Writing-original draft; Won-Chol Yang: Methodology, Project administration, Supervision, Writing-original draft; Chol-Min Jong: Data curation, Methodology, Validation; Jin-Hyok Kim: Software, Visualization.

Declaration of conflicting interests

The authors declare no conflicts of interest.

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Data availability statement

All data that support the findings of this study are included within this article.

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