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A tactile sensor for recognition of softness using interlocking structure of carbon nanoparticle- polydimethylsiloxane composite

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A R T I C L E I N F O

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A B S T R A C T

This study introduces a novel tactile sensor designed with an interlocking structure of polydimethylsiloxane (PDMS) embedded with carbon nanoparticles (CNP), aimed at enhancing the detection and differentiation of material softness. This sensor emulates the human tactile sense by detecting softness through measuring not only the pressure applied but also the transient state during material deformation to reach the indentation depth, thus providing a comprehensive softness profile. Our results reveal that the sensor effectively recognizes softness across a variety of materials and working environments, considering tolerances against operational variations. This is supported by tests conducted using a one-dimensional convolutional neural network (1D-CNN).

1. Introduction

Human skin plays a vital role in sensing external stimuli and engaging in subtle interactions with the external environment. In recent years, there has been increasing interest in research on flexible electronic devices for emulating tactile sense through human skin [1–5]. Particularly, the sense of softness is a critically important for tactile recognition. For example, one of the most challenging tasks in robotics is the ability to adjust grip force according to the softness of objects [6,7]. Moreover, the perception and recognition of object softness are also regarded as critical factors for artificial tactile technologies in fields such as augmented reality (AR), virtual reality (VR), and mixed reality (MR) fields [8–10].

Human skin is endowed with mechanoreceptors that are specialized for providing precise tactile feedback. These include four types of receptors—Merkel, Ruffini, Meissner, and Pacinian corpuscles—which integrate two primary modes of adaptation: slow (SA) and fast (FA), to process tactile information [11–13]. In particular, Merkel cells are instrumental in discerning the softness of objects by responding to static stimuli such as pressure and contact area, conveying information about softness and shape through action potentials to tactile nerves. Recently, there has been active exploration and research into tactile sensors mimicking the function of human mechanoreceptors with force (or pressure) sensors applicable to flexible architectures [14–20]. In this approach, the softness of objects is typically differentiated by reduced pressure from the applied force when a touch event occurs [21–23]. The research goal has focused on increasing sensitivity by exploring innovative materials, microstructures, and fabrication processes to develop highly sensitive sensors for the human tactile environment [24–29].

However, softness recognition is a technically delicate process, which cannot be defined solely by the single output of pressure provided by the sensor. When a force is applied to a soft material, an indentation is formed, accompanied by deformation in the direction of the force. Softness recognition requires information about the indentation process, which specifies deformation behavior according to the reduced force during the process. To reach this condition, a tactile sensor requires a specific feature that provides information about the transient interval of the indentation process. In fact, most tactile applications using force sensors are not appropriate for practically capturing this information, as they only provide the final pressure once the indentation process is completed. In this work, we develop a tactile sensor to enhance the recognition capability of softness by extracting indentation information through the introduction of an interlocking structure with carbon nanoparticles (CNP) embedded polydimethylsiloxane (PDMS).

2. Experimental

A piezo-resistive composite for the proposed sensor was prepared using a solution casting method to obtain a mixture of CNP and PDMS for the conductive polymer matrix. CNP (bulk grit content: 20 μm, primary single particle size of about 30 nm, from TIMCAL Ltd.) were used as a conductive agent. Fig. 1 displays a schematic of the fabrication

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process flow. A CNP solution was prepared with hexane and then dispersed by ultrasonication for 6 h, resulting in the formation of CNP aggregates into fragments of approximately 30–50 nm in size. The composite was mixed at 1400 rpm for 5 min using a swing planetary mixer (HSPM-1.5, HANtech Ltd.) with a revolution, twofold rotation, and shaking mixing method by adding the PDMS base and curing agent (10:1 ratio) to the CNP-hexane solution. The mixed solution was allowed to release bubbles naturally at room temperature for 30 min. Additional degassing was performed by pouring the CNP-PDMS composite into a mold (engraved with micro-sized pyramid arrays, dimensions 400 μm by 400 μm by 400 μm height) made by a 3D printer and degassing in a vacuum to remove the hexane solvent and micro-bubbles for one hour. The curing process proceeded in an oven at 60 °C for a minimum of 2 h. The conductivity of the composite depends on the weight percentage of CNP. The conductive threshold was observed at 2.0 wt%, and the conductivity increased up to 2.6×10^{-3} (S/cm) to reach solidification limit (6.0 wt%) by following the enhancement of network connectivity (see supplementary Fig. S1).

Fig. 2a shows a schematic of the devised sensor structure with the CNP-PDMS composite layers stacked in an interlocking top-bottom structure. It also displays scanning electron microscopy (SEM) images of the micro-structured pyramid arrays and a magnified view of a single pyramid of the composite created by a 3D printed mold. The top-bottom interlocking structure of the sensor utilizes the physical properties of changing contact resistance by varying the contact area of the pyramid structures of the top and bottom plates according to applied pressure. This structure not only exploits the piezo-resistive properties of the composite itself but also utilizes the changes in contact resistance, thereby showing a linear response to pressure, which is different from the common characteristic of most piezo-resistive approaches using conductive polymers. For the sensor application, we chose the composite containing 5.0 wt% of CNP (Young' modulus: 1.7 MPa) whose conductivity is 2.1×10^{-3} (S/cm) with consideration of signal stability.

Fig. 2b shows the ratio of current change ($\Delta I/I_0$) according to vertical pressure, where I_0 is current due to inherent resistance of the sensor with 5 V of the operating bias. The pressure sensing range of the sensor for response linearity is 1.5 - 100 kPa which meets the range of human tactile sense, and sensitivity within this range is 9.48 kPa^{-1} with an R-squared value of 0.991 for the linear fit (see supplementary Fig. S2 for response behavior and variation in repetitions). Note that the minimum perceptible pressure difference for humans is between 19 and 30 kPa [30]. In terms of repeatability characteristics, the sensor shows a constant output within 2 % variation during 1000 duty cycles as displayed by the error bar. Fig. 2c displays partial data of the repeatability test at 30 kPa.

3. Results and discussion

Many studies differentiate the softness of objects by measuring the pressure detected by pressure sensors. However, using this method alone is insufficient to accurately capture the softness profile of an object because softness recognition requires information about the indentation process. It would be greatly helpful to introduce a new parameter that implements information during the transient interval of the indentation process, causing deformation in shape along the direction of the force. We paid attention to sensor characteristics that effectively represent this transient moment. Fig. 3a is a schematic representation describing the deformation of the sensor along with the object when they come into contact and vertical force is applied. For soft objects, indentation depth (ΔL) varies according to the object's inherent elasticity. This characteristic is directly related to the object's softness, with softer objects exhibiting deeper indentations under the same force. When the sensor pushes an object, the response time is converted to the time interval of a transient state. The interlocking structure makes contribution for sensor response that is enhancing sensitivity comparing the case without the structure because contacting areas are gradually increased during the transient interval. This results well-defined pattern represented by the sensor.

For the measurement of softness in a contacting event, four different materials were selected: Resin, PDMS, Ecoflex, and TPU–foam, whose compression moduli (CM) are 5.01, 0.37, 0.07, 0.02 MPa at 15 kPa, respectively (see supplementary Fig. S3 for details). Fig. 3b shows the response characteristic of the sensor when a 15 kPa vertical pressure, corresponding to a gentle human touch, is applied to these four materials. Here, we observe two features: one is the saturated output response, which occurs when material deformation for indentation is complete; the other is the sensor response during the time interval of the transient state. In fact, the former feature is the same function as an ordinary force sensor. Although human touch feeling obviously distinguishes these materials by difference in softness, difference in output as a force sensor is not sufficiently large between Ecoflex and TPU–foam in spite that the proposed sensor is quite comparable sensitivity for the tactile application. On the other hand, response feature for the transient state is well defined as deformation time (t_d) when the material deforms to reach maximum indentation depth. The results for four materials are 0.64 s for Resin, 1.23 s for PDMS, 1.80 s for Ecoflex, and 3.14 s for TPU-foam. We are now able to introduce the deformation time (t_d) as a new parameter for comprehensive interpretation of an object's softness profile, in addition to the saturated output response.

Since the interlocking structure of the sensor is somewhat vulnerable for consistence in output against operating variations, it is necessary to consider for evaluation of operating tolerance. With this consideration,

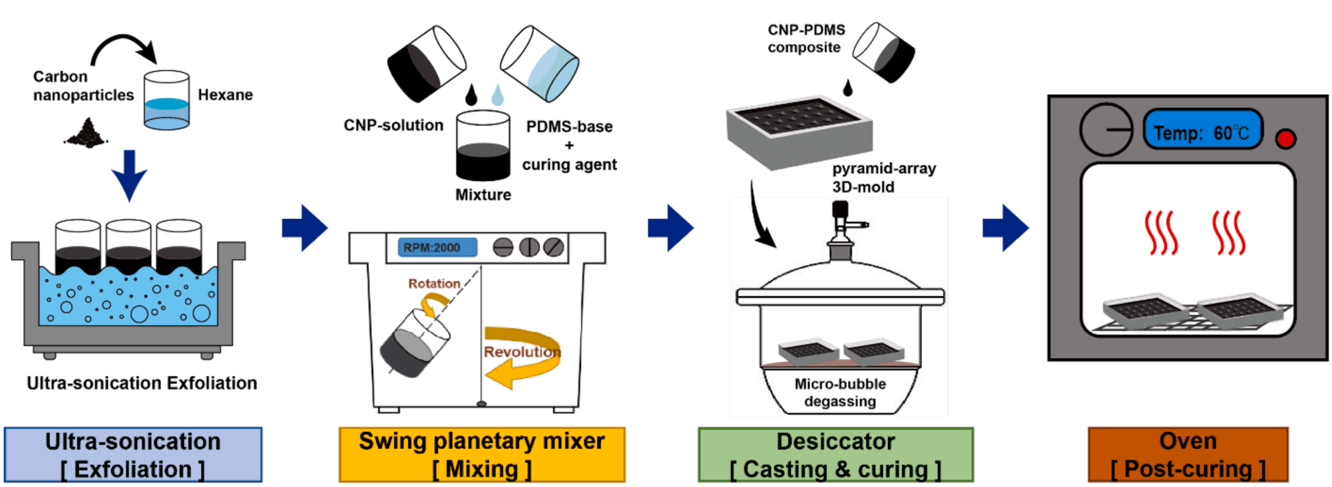

Fig. 1. Fabrication process flow for the tactile sensor, from ultra-sonication and swing planetary mixing to nano-bubble degassing and oven post-curing.

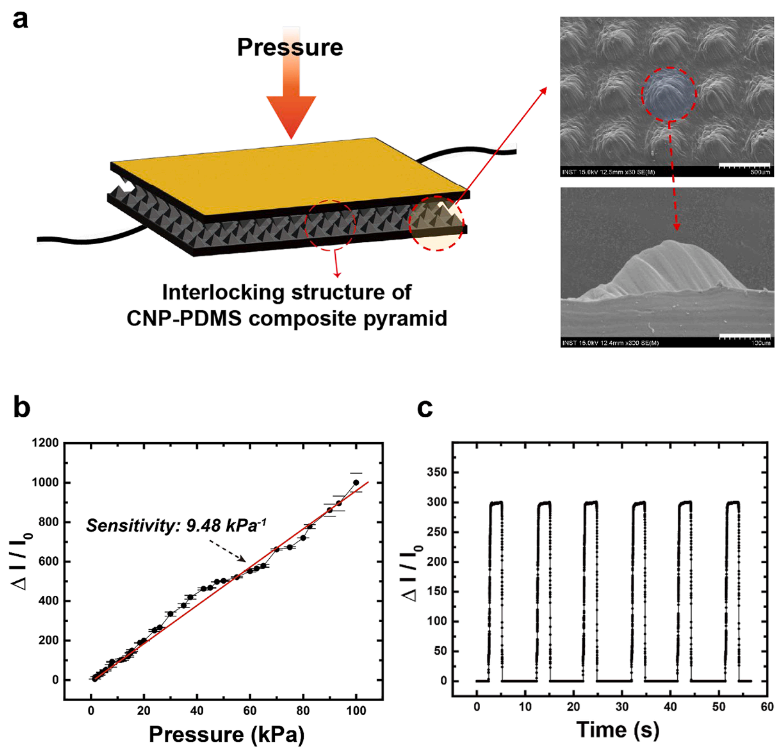

Fig. 2. Comprehensive representation of sensor design, detailing sensitivity, and repeatability characteristics: (a) Schematic representation of CNP-PDMS composite with top and bottom layers in an interlocking structure, alongside SEM images showing the magnified view of the micro-structured pyramid array. For the SEM images, the scale bar represents 500 μm in the top image and 100 μm in the bottom image. (b) The sensitivity and linearity of the sensor across a pressure range of 1.5 ∼ 100 kPa. (c) The repeatability of the sensor demonstrated under repeated static vertical pressure of 30 kPa.

comparative experiments were conducted to examine the influence of two parameters (saturated pressure and deformation time) on determination of softness using the deep neural network learning method. We collected data set for four different softness (Resin, PDMS, Ecoflex, TPU-foam) from 1100 independent measurements of sensor responses under a consistent pressure of 15 kPa for each sample. This large numbers of measurement give a situation for consideration of tolerance as well. Two data sets were separately constructed: one (D_1) is full sensor output characteristics constructing data to supply recognition result with learning of two feature vectors of the saturated pressure and the deformation time, the other (D_2) is only the saturated pressure values without information of the transient state. Experiments were separately conducted using these two types of data set (D_1 and D_2) to train and classify material softness through a 1–dimensional convolutional neural network (1D–CNN) since this neural network model is particularly suitable for applications of feature extraction from compact sequential data which we present in this work. 800 of measurement data were used for the training set and 200 for the validation set. The remaining 100 data were used for the test set. The significance of this experiment is not only to test each feature vector but also to assess error tolerance.

Fig. 4a displays the prediction results for the case of D_1 in a confusion matrix. The result shows that the four materials are perfectly distinguishable. It implies that the variances in sensor output are sufficiently tolerable to distinguish at least the four test samples. Fig. 4b shows prediction results for the case of D_2, whose overall prediction accuracy is 73 % for distinguishing each material. In detail, 100 % prediction accuracy was achieved with the relatively hard materials (Resin and PDMS), but Ecoflex had a prediction accuracy of 43 % (the remaining 57 % incorrectly predicted as PDMS), and TPU–foam showed 50 % prediction accuracy (the remaining 48 % incorrectly predicted as PDMS and 2 % as Ecoflex). This misleading comes from variations in sensor output for the saturated pressure between the sensor responses in D_2 set. In other words, only the function of pressure sensing is not sufficiently tolerable to recognize a subtle difference between materials with small CM, such as example of Ecoflex and TPU–foam. Comparison of these two approaches clearly leads to the conclusion that consideration of the transient state is also a critical factor for the tactile sensor in softness perception, as our proposed sensor demonstrates.

We performed further tests in a real operating environment with an experiment where the sensor distinguishes the softness of objects through gripping by human hand. In this situation, the interacting forces on the object are not constant for each gripping action. Ball–shaped test samples were prepared with Resin, PDMS, and Ecoflex (TPU–foam was neglected because it is difficult to make into a ball shape), as shown in Fig. 5a. Six sensors, each measuring 20 mm × 20 mm, were assembled at the tips of the five fingers and a position on the palm, as shown in Fig. 5b. These locations for sensor attachment are the expecting sites where the strongest force is applied during the ball gripping. Test data were collected from sensor output with 5 V of constant bias for every gripping of the testing ball. 200 independent measurements were made independently with separated gripping for each ball in order to including sufficient variations in sensor output. Classification was conducted for recognition test using the 1D-CNN algorithm with the sensor output data set. Among 200 data for each of the three test samples, 120, 40, and 40 data are assigned to training, validation, and test, respectively. Fig. 5c displays a confusion matrix with a classification accuracy is 80 %. In this experiment, sensing of interacting pressure cannot be a critical factor for the classification test since the applied force by gripping itself has variation. Note that, as shown for the case of Ecoflex, sensing of interacting pressure is not tolerable parameter for the softness classification even with the fixed applying force. This work infers that recognition of material softness by human tactile sense requires consideration of transient process to reach indentation depth with time scale as well. The proposed sensor catches well the consideration with definite parameter as the material deformation time. By applying this parameter, the proposed sensor is tolerably working for softness

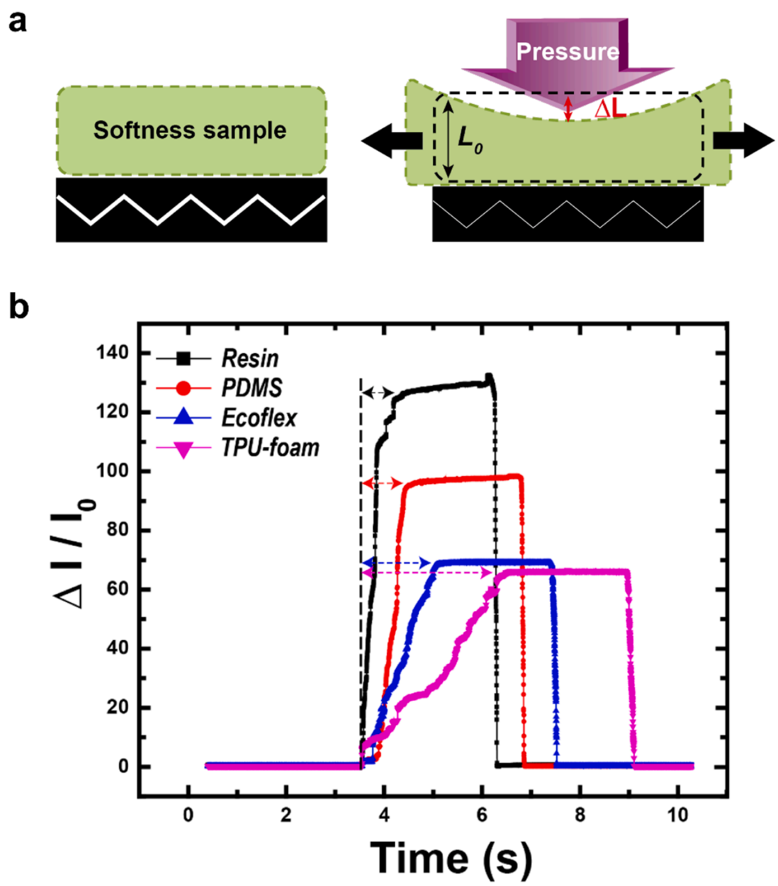

Fig. 3. Illustration and quantitative analysis of sensor response to material softness: (a) Conceptual diagram depicting the deformation of the sensor in contact with an object under the application of vertical pressure, illustrating the sensor's response to measuring the object's softness. (b) Graph showing the rate of change in current of the sensor when a 15 kPa vertical pressure is applied to four different materials, indicating the sensor's ability to detect variations in softness.

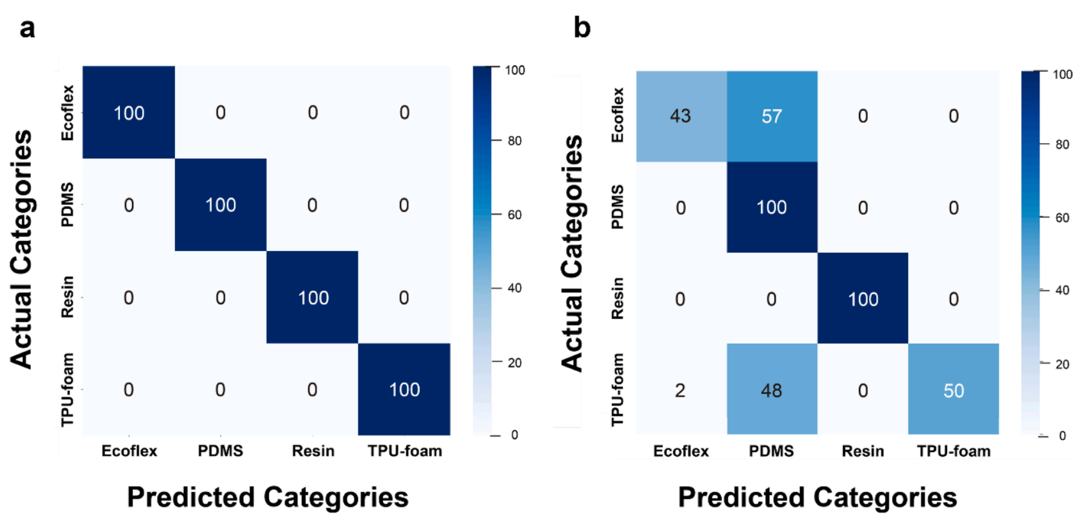

Fig. 4. Confusion matrix analysis displaying prediction results for two types of input data. (a) Shows the prediction accuracy of 100 % when the sensor output characteristics, including both feature vectors of current output and delay time, are used as input. (b) Illustrates a prediction accuracy of 73 % when only saturated current values without delay time information are used as input.

recognition of the three testing materials within 80 % accuracy in human tactile.

4. Conclusion

This study introduces and validates a novel tactile sensor utilizing an interlocking structure of a CNP-PDMS composite aimed at enhancing the recognition of material softness in tactile application. Notably, our results demonstrated that the proposed sensor technology can distinctly identify different levels of softness in materials, which is a substantial improvement over traditional pressure sensors that only measure strength of force. The sensor's capability to sense not just the pressure

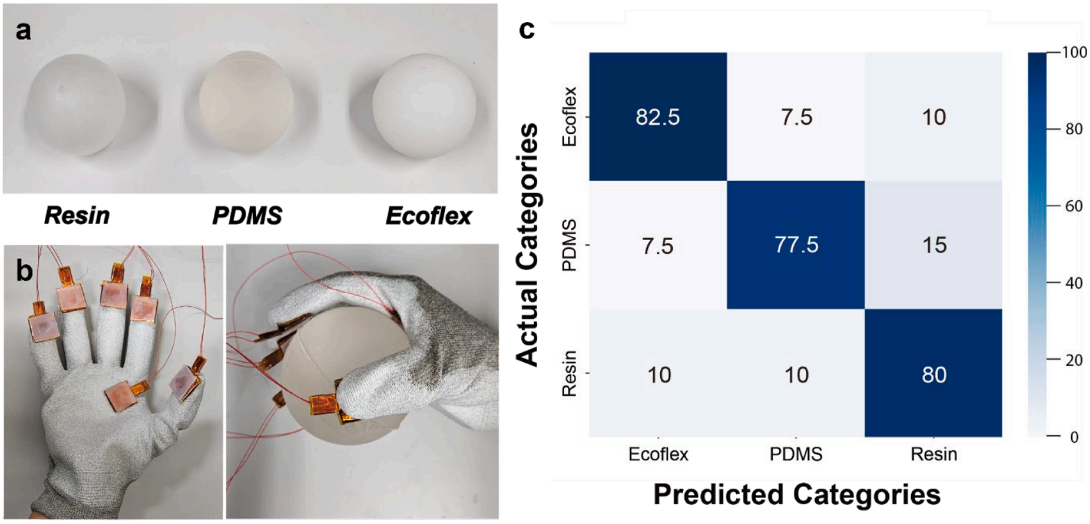

Fig. 5. This illustration depicts the process of measuring the softness of spheres made from three different materials using a glove equipped with six sensor units. (a) Ball-shaped test samples made from Resin, PDMS, and Ecoflex. (b) Six sensors (20 mm × 20 mm) positioned at the fingertips and palm of the glove, where the strongest forces are expected during ball gripping. The softness of the materials is measured during the grasping action. (c) Confusion matrix showing an 80 % classification accuracy.

but also transient state during material deformation to reach the indentation depth, which provides a more holistic understanding of an object's softness. This dual-parameter approach allows for a precise softness profile, which is crucial in applications such as robotics and prosthetics where accurate tactile feedback is essential for manipulating objects delicately and efficiently. Additionally, the sensor demonstrated excellent linearity and repeatability in our tests, affirming its potential for commercial use. The application of a 1D-CNN provided a method for evaluating the sensor's error tolerance in recognizing the softness of materials, confirming that the integration of advanced machine learning techniques can significantly enhance the sensor's performance.

In conclusion, this work not only advances the field of tactile sensing technology but also opens new avenues for the development of smart wearable devices and robotic systems that require sophisticated tactile feedback mechanisms. Future research will focus on integrating the sensor into various interactive systems to fully utilize its capabilities in practical applications.

CRediT authorship contribution statement

Sangmin Lee: Writing – original draft, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Jaewon Jang:** Validation, Investigation. **Wanjun Park:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Wanjun Park reports financial support was provided by The Korea Evaluation Institute of Industrial Technology (KEIT). Wanjun Park reports a relationship with The Korea Evaluation Institute of Industrial Technology (KEIT) that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.snr.2025.100289.

Data availability

Data will be made available on request.

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