Sensors and Materials, Vol. 38, No. 6 (2026) 3597–3610
MYU Tokyo

S & M 4522

Interactive Design of AI-integrated and Sensor-based Food Packaging with Innovative Incorporation of Arts and Crafts Elements

Ho-Sheng Chen,[1] Hui-Chen Tsai,[2] Cheng-Fu Yang,[3,4*]
Lung-Fa Wu,[5] and Jian-Chiun Liou[6**]

[1]School of Technology, Fuzhou Technology and Business University, Fuzhou, Fuiian 350715, China
[2]Center for General Education, Taiwan Steel University of Science and Technology, Kaohsiung 821, Taiwan
[3]Department of Chemical and Materials Engineering, National University of Kaohsiung, Kaohsiung 811, Taiwan
[4]Department of Aeronautical Engineering, Chaoyang University of Technology, Taichung 413, Taiwan
[5]Department of Electrical Engineering, National Yunlin University of Science and Technology Yunlin County, 640301, Taiwan
[6]School of Biomedical Engineering, Taipei Medical University, Taipei 110, Taiwan

(Received November 18, 2025; accepted June 17, 2026)

Keywords: AI design, sensing materials, smart packaging, algorithmic generation, craft aesthetics, analytic hierarchy process (AHP)

In this study, we developed an intelligent food packaging design and evaluation framework integrating AI-generated design, sensing materials, craft aesthetics, and a multi-attribute decision model. A craft-art dataset containing patterns, colors, and compositions was first established. Visual features were extracted using a Convolutional Neural Network, whereas Generative Adversarial Network and Latent Diffusion Model algorithms generated diverse patterns that preserved cultural symbols while extending modern visual appeal. Three sensing materials, namely, temperature–humidity sensing films, photochromic films, and eco-friendly substrates, were experimentally tested for response time, color difference (ΔE), mechanical strength, and food safety to ensure real-time responsiveness and stability. A user study with 30 participants compared three prototypes: (1) conventional packaging, that is, packaging without AI-generated design or sensing-interactive functionality, (2) algorithm-generated packaging, and (3) algorithm sensor-interactive packaging. Participants evaluated visual aesthetics, interactivity, and cultural identity. By using Analytic Hierarchy Process and Fuzzy-Technique for Order Preference by Similarity to Ideal Solution for multi-attribute analysis, the sensor-interactive packaging achieved the best performance across Structural Similarity Index Measure, Frechet Inception Distance, color harmony, and user rating (correlation coefficient = 0.670), outperforming the others. The findings confirm that integrating AI-driven generative design with sensor-based materials enhances the aesthetic and interactive experience of packaging. The proposed framework provides a quantifiable and practical evaluation model for cultural-creative design, offering broad applicability to food, cultural, and sustainable packaging industries and supporting the advancement of smart packaging and cultural innovation.

*Corresponding author: e-mail: cfyang@nuk.edu.tw
**Corresponding author: e-mail: jcliou@tmu.edu.tw
https://doi.org/10.18494/SAM6060

ISSN 0914-4935
https://myukk.org/

1. Introduction

Food packaging not only fulfills basic functions such as product protection, storage, and transportation but has also become an essential medium for shaping brand identity and conveying cultural value. With the diversification of markets, the focus of packaging design has shifted from pure functionality to a multidimensional integration of function, aesthetics, and culture. In the food industry, consumers' expectations for packaging have moved beyond practicality, emphasizing sensory experience and emotional connection.(1) In recent years, as consumers increasingly demand higher standards for food safety and quality, the application of sensing materials in smart food packaging has become a research hotspot. Temperature and humidity sensing materials can monitor environmental conditions in real time and indicate changes through color variations or optical signal transformations, thereby visualizing food quality. For example, Tong *et al.* developed a cellulose/TiO_2 composite film that exhibits distinct optical changes under varying humidity conditions, enabling the effective visualization of food storage environments.(2) Similarly, Zhang *et al.* proposed an edible humidity indicator (EHI) that uses food-grade polymers to produce irreversible changes under high humidity, allowing consumers to intuitively assess food freshness.(3)

The application of smart sensing materials, including temperature–humidity sensing films, gas-sensitive layers, and photochromic films, has opened new possibilities for packaging innovation. These materials can dynamically reflect environmental variations, enhancing safety monitoring and interactive functionality. They not only improve food preservation but also introduce real-time perceptual and interactive dimensions into design. However, achieving deep integration between sensing technologies and visual-aesthetic design remains an unresolved challenge. Furthermore, smart films and composite sensing materials have been widely used for detecting gases, pH values, and volatile organic compounds, providing early warnings of food spoilage. Although these studies have established a solid technical foundation for smart packaging in food safety monitoring, current research still focuses primarily on sensing accuracy and stability, with relatively limited attention to the integration of sensing functionality with design aesthetics and cultural value.

The development of algorithmic design has also provided strong momentum for innovation in packaging. Deep learning techniques, such as Generative Adversarial Networks (GANs)(4) and Latent Diffusion Models (LDMs),(5) as well as multi-criteria decision-making (MCDM) methods such as the Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS),(6) have been widely applied to image generation, design recommendation, and user experience analysis. Algorithm-driven design processes can significantly improve efficiency by integrating data analytics to optimize both aesthetic quality and interactive performance, thereby achieving intelligent and adaptive design decisions. Generative algorithms, represented by GANs and LDMs, have become powerful tools in contemporary design. These models can efficiently generate design patterns with specific styles and structural features, and have been extensively applied in product design, art creation, and brand visual identity development.

In design decision support, MCDM frameworks such as AHP and TOPSIS have been employed for packaging material selection, user preference analysis, and design scheme evaluation. These methods provide a quantitative foundation for the overall process of design generation, evaluation, and optimization. However, most existing applications remain focused on product functionality and efficiency, while the integration of cultural elements and interactive experiences in algorithmic design still requires further exploration and development. Furthermore, craft aesthetics, as an essential carrier of Chinese culture, embodies a rich system of patterns, colors, and formal symbols. Integrating these elements into food packaging design not only enhances visual aesthetics but also conveys cultural value and brand identity.(7,8) Craft aesthetics, characterized by strong symbolism and recognizability, can deepen consumers' emotional resonance and strengthen cultural connections with the product. Li *et al.* further emphasized that packaging design incorporating cultural symbols can effectively enhance brand differentiation and improve international market competitiveness.(8)

However, most current applications of craft aesthetics remain limited to static decorative expressions, lacking deep integration with algorithmic design technologies and intelligent sensing materials. This limitation prevents the full realization of craft aesthetics' cultural potential in intelligent and interactive packaging systems. By coupling traditional artistic elements with sensor-based materials and AI-driven generative algorithms, future packaging design can achieve both cultural depth and technological innovation, aligning with the smart and interactive design vision central to *Sensors and Materials*. On the basis of the above literature, three major research gaps and challenges can be identified.

(1) Insufficient integration of functionality and culture: Current studies on sensing materials primarily focus on safety monitoring and physical performance, with limited consideration of cultural and aesthetic integration.

(2) Limited cultural contextualization of algorithmic applications: Although algorithms demonstrate strong capabilities in design generation and optimization, their use in food packaging and cultural integration remains at an early stage.

(3) Static application of craft aesthetics: The lack of integration with interactive technologies and intelligent design prevents the full realization of craft aesthetics' cultural value.

The core challenge of this study lies in effectively integrating algorithmic generation, sensing materials, and craft aesthetics to establish an innovative food packaging design model that combines functionality, safety, and cultural value. This integrative strategy not only challenges traditional design paradigms but also opens new directions for the development of intelligent and interactive packaging design aligned with the goals of compositions of sensors and materials. In this study, we particularly emphasize the interdisciplinary integration of AI-driven design generation, sensor-based responsive materials, and arts-and-crafts aesthetics in food packaging applications. Unlike conventional packaging studies that focus primarily on functionality or visual appearance alone, the proposed framework combines intelligent algorithmic generation with interactive sensing mechanisms to create culturally expressive and environmentally responsive packaging systems. This integration reflects the emerging development trend of smart packaging toward interactive, data-driven, and culturally meaningful design. More importantly, in this study, we extend beyond conventional packaging appearance design by investigating how responsive sensing materials can be integrated with AI-generated visual structures to establish environmentally perceptive and interactive packaging systems. The proposed framework emphasizes the functional interaction among sensing response behavior, material stability, and intelligent visual communication, thereby providing a potential development direction for future multifunctional sensing materials and sensor-integrated smart packaging technologies. Despite recent progress in smart packaging and AI-assisted design, challenges still remain in achieving effective integration among sensing functionality, cultural aesthetics, and interactive user experience within a unified packaging framework. To address these issues, we combine algorithmic image generation, sensor-responsive materials, and multi-attribute evaluation methods to establish an intelligent and culturally oriented food packaging model. Nevertheless, this work is still limited by the relatively small participant group and laboratory-scale validation conditions. Future studies should further investigate large-scale manufacturing feasibility, long-term sensing stability, and broader consumer evaluations under real commercial environments.

2. Methodology

In this study, we aim to establish an innovative food packaging design and evaluation framework that integrates algorithmic design, sensing materials, and craft aesthetics. The overall methodology is structured into five major stages, encompassing data construction, algorithmic modeling, material testing, user experiments, and multi-criteria decision analysis, ensuring the framework's systematicity, operability, and reproducibility. The research process consists of the following five stages.

(1) Craft aesthetics data construction: Collection and organization of traditional patterns, color schemes, and compositional structures to build a standardized dataset.
(2) Algorithmic modeling and design generation: Application of Convolutional Neural Networks (CNNs), GANs, and LDMs models to extract pattern features and generate design outputs.
(3) Sensing material performance testing: Selection of three types of sensing material, namely, temperature–humidity sensing films, photochromic films, and biodegradable substrates, for laboratory testing and characterization.
(4) User experiment and interaction evaluation: Development of three packaging prototypes, followed by questionnaire surveys and behavioral observations to assess visual perception, interactivity, and emotional response.
(5) Evaluation and optimization analysis: Determination of indicator weights using AHP, and ranking of design alternatives through Fuzzy-TOPSIS to optimize final design performance.

The dataset was constructed from three primary sources.

(1) Museums and digital archives: Traditional craft patterns from ceramics, lacquerware, textiles, and related artifacts.
(2) Craft catalogues and design monographs: Folk art elements such as paper-cutting motifs and calligraphic ornamentations.
(3) Food packaging cases: Contemporary applications in tea, pastry, and alcoholic beverage packaging.

The dataset encompasses pattern morphology, traditional and food-related color palettes, and compositional structures, comprising a total of 1260 images, as summarized in Table 1. All images were standardized to a resolution of 512 × 512 pixels and manually annotated for key visual features, as shown in Table 2.

To preserve cultural semantics and enhance design diversity, we integrate multiple deep learning algorithms for feature extraction and image generation. CNN is employed to extract features such as pattern edges, color distribution, and symmetry.[9] GAN is utilized to generate innovative designs with consistent stylistic features,[4] whereas LDM enables the creation of high-resolution patterns through denoising in the latent space.[5] The evaluation indicators for the algorithmic design performance are presented in Table 3 and Fig. 1.

In this study, we selected three representative types of sensing material. The first is a temperature–humidity sensing film composed of a cellulose/TiO_2 composite, which exhibits high humidity sensitivity.[1] The second is a photochromic film that changes color in response to ultraviolet and visible light, serving as an interactive trigger interface.[3] The third is a biodegradable substrate that offers both environmental sustainability and structural strength while meeting food safety standards.[2] All response tests were conducted under controlled conditions of 25 ± 1°C, 30–90% relative humidity, and 0–1000 lx illumination. The performance evaluation metrics for the sensing materials are presented in Table 4. Temperature and humidity conditions were monitored using a digital thermo-hygrometer sensor system with an accuracy of ±0.5 °C and ±2% RH. The humidity-response behavior of the sensing films was evaluated inside a programmable humidity chamber, whereas optical response characteristics and color variation (ΔE) were measured using a portable spectrometer and a digital colorimeter, respectively, under controlled illumination conditions. Ultraviolet-induced photochromic responses were generated using a 365 nm UV LED irradiation source with adjustable optical intensity. In addition, the tensile strength and mechanical stability of the biodegradable substrates were characterized using a universal tensile testing machine operated under standard laboratory conditions.

To verify the practical effectiveness of different design strategies, we developed three types of packaging prototype.

(1) Conventional packaging: In this study, “conventional packaging” refers to food packaging with designs that do not incorporate AI-generated visual structures, sensing materials, or interactive functionalities. This version adopts standard packaging styles commonly used in existing commercial food products and serves as the baseline control group.

Table 1
Structure of the craft aesthetics dataset.

Category	Sub-item	Description	Number of images
Traditional craft patterns	Ceramics, embroidery, woodcarving, folk art	Dragon–phoenix, lotus, cloud motifs, New Year prints	545
Color systems	Traditional palettes, food-related colors	Vermilion, ocher yellow, azurite blue, brownish green, golden red	318
Compositional principles	Geometric symmetry, continuous patterns, central composition	Key-fret, wave, border motifs	158
Packaging cases	Integration of traditional and modern design	Tea canisters, chocolate × ink-painting fusion	239

Table 2
(Color online) Catalogues of craft aesthetics used in this study.

Sub-items	Typical case	
Ceramic pattern		
Weaving and embroidery patterns		
Wood carving, lacquerware, metalworking		
Folk art		

(2) Algorithmic design packaging: This prototype utilizes CNN, GAN, and LDM to extract stylistic and structural features from the traditional craft pattern dataset, generating modern design patterns with enhanced symmetry and color harmony for packaging applications. The algorithmic framework, composed of CNN, GAN, and LDM, is used to evaluate the visual impact of algorithm-generated design.

Table 3
Evaluation indicators for the algorithmic design performance.

Evaluation aspect	Description	Ideal value	Reference
Image sharpness	Structural similarity index	Closer to 1 is better	Ref. 10
Image quality	Signal-to-noise ratio	Higher is better	Ref. 11
Pattern fidelity	Frechet inception distance	Lower is better	Ref. 12
Color harmony	Degree of visual coherence	Higher is better	Ref. 13
Subjective perception	User evaluation on Likert scale	> 4 points	Ref. 14

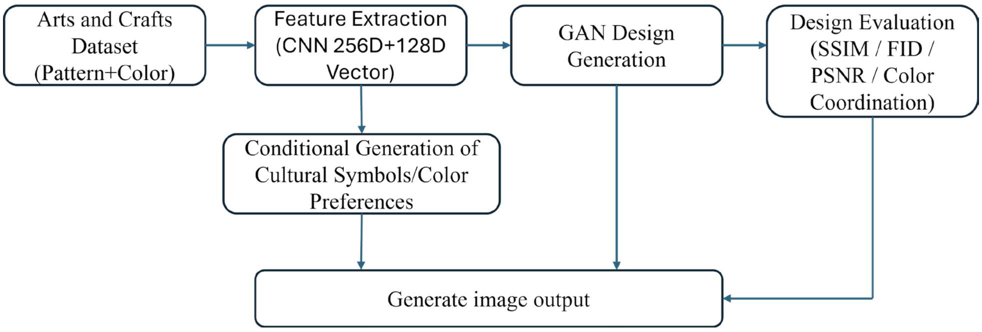


Fig. 1. (Color online) Flowchart of the algorithmic generation process (CNN feature extraction → GAN / LDM → evaluation).

Table 4
Performance evaluation indicators of sensing materials.

Material	Test item	Test method	Evaluation indicator	Unit
Temperature–humidity sensing film	Humidity response	Humidity chamber + spectrometer	Response time, sensitivity	s/%
Photochromic film	Light response	UV irradiation + photography	ΔE, color-change rate	ΔE/s
Biodegradable substrate	Structural and safety test	Tensile test + dissolution measurement	Tensile strength, dissolution amount	MPa/mg

(3) Algorithmic sensor-interactive packaging: Building upon the algorithmic design packaging, this prototype integrates temperature–humidity sensing films and photochromic layers to enable real-time visual responses to environmental changes. This integration enhances interactivity, user engagement, and brand recognition. The technical framework, combining CNN, GAN, LDM, and sensing materials, is employed to assess improvements in interactive experience and emotional identification.

A total of 30 participants were recruited from Dongguan City University and local consumers in Dongguan, Guangdong Province, China. Recruitment was conducted through campus announcements, online invitation platforms, and voluntary participation to ensure diversity in demographic characteristics and consumer perspectives. Detailed demographic and background information of the 30 participants is summarized in Table 5. The participant group consisted of 16 females and 14 males, with ages ranging from 20 to 45 years (mean age = 31.6 years, SD = 6.8). In terms of educational background, twenty participants held a bachelor's degree or higher,

Table 5
Demographic characteristics of participants.

Characteristic	Category	No.	%
Gender	Male	14	46.7
	Female	16	53.3
Age	20–29	12	40.0
	30–39	11	36.7
	40–45	7	23.3
Education	Secondary/Vocational	10	33.3
	Bachelor's or above	20	66.7
Design experience	Yes	8	26.7
	No	22	73.3

whereas ten participants had completed secondary or vocational education. To better reflect realistic consumer preferences and user perceptions, participants were not restricted to design-related disciplines or professional backgrounds. Among the participants, eight individuals had prior experience in design, visual arts, packaging, or cultural and creative industries, whereas the remaining twenty-two participants represented general consumers without formal design training or professional creative experience. Before the experiment, all participants were informed of the objectives, procedures, and evaluation process of the study and subsequently provided informed consent. Participation was entirely voluntary, anonymous, and conducted without financial compensation to minimize potential bias and ensure authentic user feedback.

A five-point Likert scale, as shown in Table 6, was employed to evaluate three key dimensions: visual aesthetics, focusing on the harmony of patterns and colors; interactive performance, assessing the intuitiveness and recognizability of sensor-based changes; and emotional identification, examining participants' understanding of cultural symbols and their emotional responses, as shown in Table 7. Data were collected through Likert-scale questionnaires, behavioral observations (including viewing duration and interaction frequency), and semi-structured interviews.

To integrate both objective and subjective evaluation results, we employed AHP and TOPSIS to construct a multi-criteria evaluation and data analysis model. In the first step, AHP was used to determine expert weights: five experts conducted pairwise comparisons of the five major evaluation indicators, from which the weight vector was calculated and consistency was verified ($CR < 0.1$). In the second step, TOPSIS was applied for design ranking: the Likert-scale questionnaire results were transformed into a decision matrix, and the closeness coefficient (CC) was calculated for each design alternative to perform ranking and optimization analysis.[19]

3. Results and Discussion

In this study, we employed CNN in combination with GAN and LDM for pattern feature extraction and image generation, effectively preserving the structural symmetry and color harmony of craft aesthetics while extending them into a modern design vocabulary. Figure 2 presents a comparison between the original craft pattern and the algorithmically generated design, demonstrating the model's capability to retain structural features while enabling creative

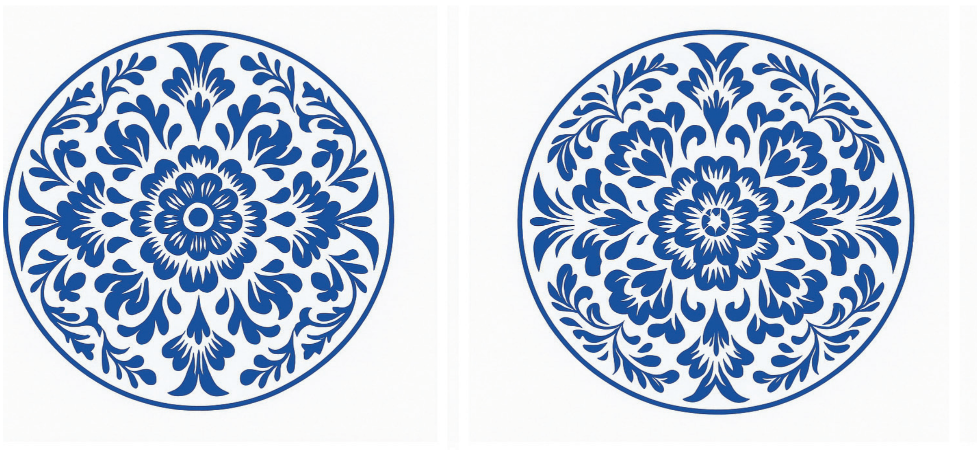
Table 6
Likert-scale questionnaire items used in the user experiment.

Dimension	Item code	Questionnaire item
Aesthetic perception	AP1	The packaging design is visually attractive.
	AP2	The color scheme is harmonious and pleasing.
	AP3	The craft-art patterns enhance the visual appeal of the packaging.
	AP4	The overall design appears innovative and aesthetically pleasing.
Interactive performance	IP1	The sensing response is easy to observe.
	IP2	The color-changing effect is clear and understandable.
	IP3	The packaging provides an interesting interactive experience.
	IP4	The sensing function improves my understanding of the product condition.
Emotional preference	EP1	The packaging conveys cultural characteristics effectively.
	EP2	The craft-art elements increase my emotional connection to the product.
	EP3	The packaging enhances my impression of the brand.
	EP4	I would be willing to purchase a product with this packaging design.

Response scale: 1 = Strongly disagree; 2 = Disagree; 3 = Neutral; 4 = Agree; 5 = Strongly agree.

Table 7
User experience evaluation indicators.

Dimension	Secondary indicator	Example question	Reference
Aesthetic perception	Color harmony, pattern recognizability	Is the color combination visually appealing?	Refs. 14 and 15
Interactive experience	Response clarity, operational convenience	Is the interactive effect easy to observe?	Ref. 16 ISO 9241
Emotion and culture	Cultural identification, emotional pleasure	Does the design evoke feelings of pleasure or curiosity?	Refs. 17 and 18



(a) (b)

Fig. 2. (Color online) Comparison between (a) the original craft pattern and (b) the algorithmically generated design.

variation. Quantitative results indicate that the generated images achieved an average SSIM of 0.87 with the original patterns, reflecting high structural similarity. The FID values show that the generated image distribution closely matches the real dataset, and the color harmony index also reached a satisfactory level, demonstrating strong visual consistency.

In this study, three types of sensing material were selected for laboratory testing under controlled conditions: temperature–humidity sensing films, photochromic films, and biodegradable substrates. The temperature–humidity sensing films demonstrated stable color changes under 40–80% relative humidity at 25 °C, with an average response time of approximately 12 s, indicating sufficient sensitivity and responsiveness for the real-time monitoring of environmental conditions. The photochromic films exhibited a Δ*E* greater than 20 under 2 mW/cm^2 UV irradiation, with color-change completion in less than 5 s, highlighting their potential as intuitive visual feedback mechanisms for interactive packaging designs. The biodegradable substrates showed a tensile strength of 25 MPa while meeting food-contact safety standards, confirming their suitability as structurally reliable and environmentally sustainable packaging materials.

Collectively, these performance results suggest that the selected sensing materials are highly compatible with the requirements of smart packaging, offering both functional responsiveness and interactive capabilities. The integration of these materials enables the packaging to provide real-time sensory feedback, enhancing consumer engagement and potentially improving product safety and quality monitoring, which are critical considerations in modern food packaging applications. Figure 3 presents the response curves of the materials under environmental stimuli, showing that the humidity-sensing films maintain stable color changes across the 40–80% RH range, the photochromic films respond rapidly to UV exposure, and the biodegradable substrates provide a stable structural foundation. These results demonstrate that combining responsive sensing films with safe and durable substrates can not only enhance the functional and interactive capabilities of food packaging but also enable real-time sensory feedback, which is crucial for improving consumer engagement, monitoring product quality, and supporting intelligent packaging applications. From the perspective of sensors and materials research, these

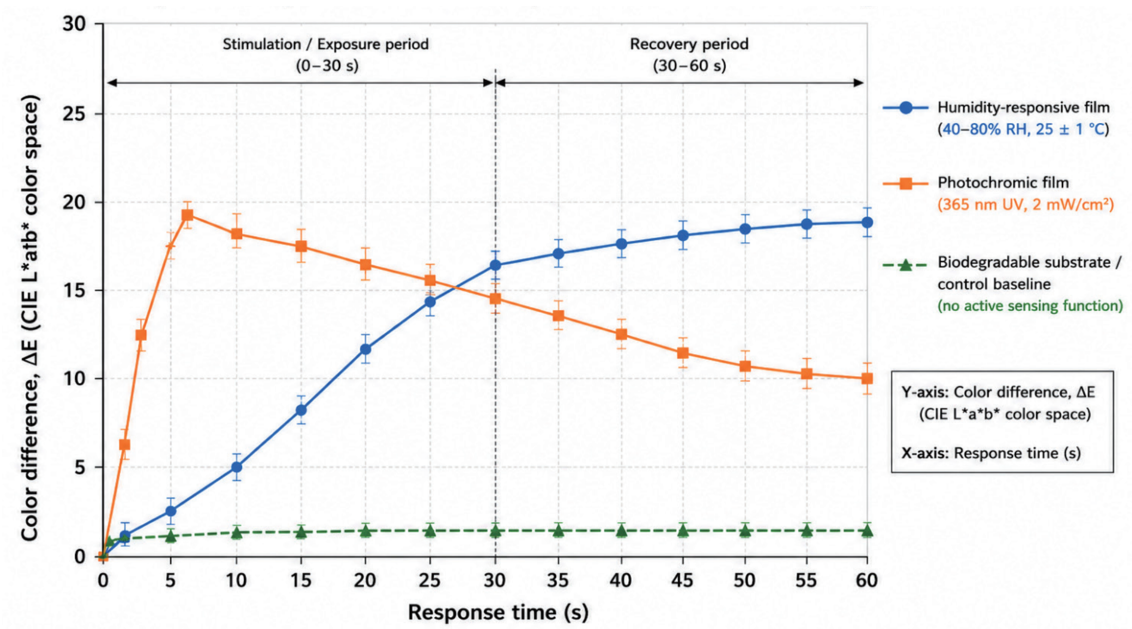


Fig. 3. (Color online) Time-dependent colorimetric response curves of the three sensing-related materials.

findings further demonstrate that responsive films and sensor-based substrates can serve not only as packaging components but also as interactive sensing interfaces capable of real-time environmental perception and visual feedback. The integration strategy proposed in this study may provide useful guidance for the future development of multifunctional sensing materials, smart food-monitoring films, and human-interactive packaging sensors.

The humidity-responsive film was evaluated under controlled environmental conditions of 25 ± 1 °C and 30–90% RH. During the experiments, temperature was maintained at a constant level to minimize thermal interference and isolate the humidity-dependent optical response of the sensing material. Because the primary objective of this study was to investigate interactive packaging behavior and visual-feedback performance, humidity response was selected as the principal evaluation parameter. Future studies will further investigate the combined effects of temperature and humidity under refrigerated (4 °C), ambient (25 °C), and elevated-temperature (40 °C) storage environments to better simulate practical food-packaging conditions. Figure 3 presents the time-dependent colorimetric response behaviors of the three sensing-related materials under different environmental stimuli, and all data were obtained from the laboratory measurements. The *X*-axis represents response time (s), whereas the *Y*-axis represents color difference (ΔE) calculated in the CIE Lab* color space, and ΔE is measured using a colorimeter (Konica Minolta CR-400). The blue curve corresponds to the humidity-responsive film tested under 40–80% RH at 25 ± 1 °C, showing stable and reversible color transitions with increasing humidity, thereby confirming its reliability for moisture monitoring applications. The orange curve represents the photochromic film under 365 nm UV irradiation at 2 mW/cm^2, exhibiting a rapid colorimetric response within 5 s and demonstrating high sensitivity to optical stimuli for interactive packaging applications. The green dashed curve corresponds to the biodegradable substrate/control baseline, which showed minimal color variation because of the absence of active sensing functionality, while still maintaining a stable structural support. Error bars indicate the standard deviation (n = 3). All data were obtained from original laboratory measurements conducted in this study using a colorimeter under controlled experimental conditions. Collectively, these results demonstrate that the integration of responsive sensing films with biodegradable substrates can provide environmental detection, optical signaling, and structural support simultaneously, highlighting the potential of multifunctional smart packaging systems.

To investigate how different packaging designs affect user perception, thirty participants were invited to evaluate three types of packaging using a five-point Likert scale: (i) conventional packaging, (ii) algorithmically generated packaging, and (iii) algorithmic sensor-interactive packaging. The results demonstrated that sensor-interactive packaging achieved the highest mean score in visual aesthetics (4.506), significantly exceeding that of conventional packaging (3.549, p = 0.021). In terms of interactivity performance, the sensor-interactive packaging exhibited a significant advantage over the other two designs ($p < 0.001$), indicating that the sensing layer effectively enhanced user engagement and responsiveness to environmental stimuli. Regarding emotional and cultural identification, both algorithmic and sensor-interactive packaging designs scored higher than conventional packaging (p = 0.036), suggesting a stronger connection between cultural symbolism and sensory experience. These results, summarized in Table 8, indicate statistically significant differences across all three dimensions: aesthetic

Table 8
Statistical results of the user experiment for the three packaging designs.

Evaluation dimension	Conventional packaging (*Mean* ± *SD*)	Algorithmically generated (*Mean* ± *SD*)	Sensor-interactive (*Mean* ± *SD*)	Significance test (p-value)
Visual aesthetics	3.549 ± 0.720	4.227 ± 0.559	4.506 ± 0.496	0.021
Interactive performance	2.782 ± 0.818	3.843 ± 0.717	4.639 ± 0.474	<0.001
Emotional identification	3.346 ± 0.737	4.029 ± 0.623	4.128 ± 0.579	0.036

perception, interactive performance, and emotional resonance. The findings reinforce the concept that sensor-augmented materials can not only improve functional responsiveness but also enhance users' perceptual and emotional interaction with intelligent packaging systems, aligning with the broader objectives of sensor-driven material innovation.

To integrate both objective performance metrics and subjective user experience, we employed AHP to determine the weighting of evaluation indicators—SSIM (0.25), FID (0.20), Color Harmony (0.20), CAM (0.15), and User Rating (0.20)—followed by TOPSIS for comprehensive ranking analysis. Table 9 presents the original evaluation metrics for the three design types, whereas Table 10 summarizes the final ranking outcomes. The sensor-interactive packaging achieved the highest *CC* (= 0.6701), followed by the algorithm-generated design packaging (*CC* = 0.5385), with conventional packaging scoring lowest (*CC* = 0.0000). These findings are consistent with the user evaluation results, confirming that the integration of sensor-driven interaction significantly enhances both perceptual and experiential qualities. The combined AHP-TOPSIS framework effectively bridges quantitative image-based assessments with qualitative human feedback, demonstrating its feasibility and reliability in evaluating sensor-integrated packaging systems. This approach highlights how data-driven modeling and human-centered evaluation can jointly guide the design optimization of smart sensing materials and interactive packaging.

The findings of this study demonstrate the potential of integrating AI, sensor materials, and multi-attribute decision analysis to enhance both aesthetic and functional dimensions of modern packaging design. The AI-generated designs, developed through CNN-GAN-LDM modeling, successfully preserved the structural and chromatic characteristics of traditional craft motifs, resulting in a significant improvement in visual appeal and cultural expressiveness. The incorporation of temperature–humidity responsive films and photochromic layers further endowed the packaging with real-time environmental responsiveness, transforming it into an interactive medium that strengthens user engagement and reinforces brand identity. Moreover, the application of AHP and TOPSIS provided a robust multi-attribute decision framework that effectively integrated algorithmic performance metrics with subjective user evaluations. The consistency between the ranking results and user experience data verifies the reliability and interpretive value of the proposed assessment model. This interdisciplinary approach illustrates how the convergence of cultural heritage, sensing technology, and intelligent evaluation systems can lead to innovative design methodologies. From an industrial perspective, the proposed framework offers practical potential for use in tea, pastry, and cultural gift packaging, providing

Table 9
Original evaluation indicator values of the three design types.

Category	SSIM	FID	Color_Harmony	CAM	User_Rating
Conventional	—	—	68.5	0.58	3.226
Algorithmic	0.89	28.7	82.1	0.77	4.033
Algorithmic sensor-interactive	0.90	24.5	86.4	0.82	4.424

Table 10
TOPSIS ranking results. D^{+}: distance from the positive ideal solution, D^{-}: distance from the negative ideal solution, CC: closeness coefficient

Category	D^{+}	D^{-}	CC	Rank
Conventional	0.5821	0.0000	0.0000	3
Algorithmic	0.2647	0.3088	0.5385	2
Algorithmic sensor-interactive	0.2000	0.4062	0.6701	1

a replicable model for the development of sensor-augmented smart packaging that bridges aesthetic design and technological functionality.

From a practical perspective, the proposed framework also demonstrates promising cost-effectiveness because the sensing materials employed in this study are compatible with existing packaging manufacturing processes and do not require highly complex fabrication procedures. Moreover, AI-assisted generative design can reduce manual design workload and improve development efficiency, thereby supporting the practical commercialization potential of intelligent packaging systems. Beyond food packaging applications, the proposed framework may also be extended to other fields involving intelligent sensing materials and interactive design, such as cosmetic packaging, pharmaceutical packaging, cultural and creative products, smart labels, wearable sensing devices, and interactive consumer products. The integration strategy combining AI-assisted generative design with responsive sensing materials provides a flexible development framework for future smart-material and human-interaction applications.

4. Conclusions

In this study, we focused on the integration of AI-generated design, sensor materials, and multi-attribute decision models to evaluate three types of packaging prototype: conventional packaging, algorithmically generated design packaging, and algorithmic sensor-interactive packaging. We employed image analysis, material performance testing, and user experiments, and synthesized the results using AHP and TOPSIS for comprehensive ranking. Findings indicated that this technological fusion strategy enhances visual aesthetics, interactivity, and emotional value while providing precise decision support and establishing a cross-disciplinary evaluation framework with significant applicability in smart packaging design. We also revealed several key insights. AI-driven algorithmic design, implemented through CNN-GAN-LDM modeling, successfully extracted and generated craft motif features, significantly outperforming conventional packaging in metrics such as SSIM, FID, and color harmony, achieving the design objective of preserving cultural elements while integrating contemporary visual language. Sensor materials, including photochromic films and temperature–humidity responsive membranes, provided real-time visual feedback to environmental changes, resulting in significantly higher interactivity scores than other groups (p < 0.001), thereby enhancing user engagement and brand recognition. User experiments further demonstrated that cultural symbols elevated emotional brand value, and when combined with sensor interactivity, produced a dual emotional gain effect that strongly affected user preference. The AHP and TOPSIS multi-attribute decision model effectively reflected these design advantages, with the final ranking showing the sensor-interactive packaging leading (CC = 0.670), followed by the algorithmically generated design packaging (CC = 0.539), and the conventional packaging (CC = 0.000). This ranking aligns with subjective user evaluations, confirming the reliability and practical utility of the integrated assessment framework. Future work should focus on large-scale commercialization, long-term material stability, and broader cross-cultural user evaluations to further improve the practical applicability of AI-integrated smart food packaging systems. Overall, the results highlight the potential of combining AI design, sensor technologies, and structured decision models to advance culturally informed, interactive, and data-driven smart packaging solutions.

Acknowledgments

This work was supported by Summit-Tech Resource Corp. and by projects under Nos. NSTC-114-2314-B-038-083, MOST-111-2221-E-038 -007 -MY2, MOST-111-2221-E-038 -004 -MY3, 109-TMU-NTUST-109-10, NSTC 113-2221-E-390-011.

References

1 C. G. Otoni, P. J. P. Espitia, R. J. Avena-Bustillos, and T. H. McHugh: Food Res. Int. **83** (2016) 60.
2 X. Tong, H. Wang, H. Ding, J. Li, H. Zhao, Z. Lin, H. Xi, and X. Zhang: Nanomaterials **12** (2022) 1970.
3 C. Zhang, X. Liu, and S. Chen: ACS Appl. Polym. Mater. **5** (2023) 767.
4 I. J. Goodfellow, J. Pouget-Abadie, M. Mirza, B. Xu, D. Warde-Farley, S. Ozair, A. Courville, and Y. Bengio: Proc. 28th Int. Conf. Neural Inf. Process. Systems **2** (2014) 2672–2680.
5 R. Rombach, A. Blattmann, D. Lorenz, P. Esser, and B. Ommer: Proc. IEEE/CVF Conf. Computer Vision and Pattern Recognition (2022), 10684–10695.
6 M. Behzadian, R. B. Kazemzadeh, A. Albadvi, and M. Aghdasi: Expert Syst. Appl. **39** (2012) 13051.
7 How Culture Influences Packaging Aesthetics: A Global Design Imperative I - Jarsking: https://www.jarsking.com/how-culture-influences-packaging-aesthetics-a-global-design-imperative-i/ (accessed April 2025).
8 Y. Li, L. Zhang, and S. Chen: J. Des. Stud. **18** (2023) 52.
9 A. Krizhevsky, I. Sutskever, and G. E. Hinton: Commun. ACM **60** (2017) 84.
10 Z. Wang, A. C. Bovik, H. R. Sheikh, and E. P. Simoncelli: IEEE Trans. Image Process. **13** (2004) 600.
11 A. Horé and D. Ziou: 2010 20th Int. Conf. Pattern Recognition (2010) 2366–2369.
12 M. Heusel, H. Ramsauer, T. Unterthiner, B. Nessler, and S. Hochreiter: Proc. 31st Int. Conf. Neural Information Processing Systems (NIPS, 2017) 6629–6640.
13 L. C. Ou and M. R. Luo: Color Res. Appl. **31** (2006) 191.
14 C. Spence: Cell **161** (2015) 24.
15 D. A. Norman: Emotional Design: Why We Love (or Hate) Everyday Things (Basic Books, New York, USA, 2004).
16 S. J. Ahn: J. Des. Res. **18** (2020) 145.
17 P. Hekkert: Psychol. Sci. **48** (2006) 157.
18 P. Desmet: Int. J. Des. **1** (2007) 57.
19 T. L. Saaty: The Analytic Hierarchy Process (McGraw-Hill, New York, USA, 1980).