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Optimization of Thermochromic Printing Inks for Functional Temperature Indicators

ABSTRACT

Thermochromic printing inks are functional graphic materials widely used in various applications, including the development of temperature indicators. For such systems, material compatibility and the optimization of thermochromic ink properties are essential to ensure reliable temperature indication. In this research, a functional printed indicator was developed for monitoring the temperature conditions of insulin therapy during storage and use. The multilayer indicator consists of a pictogram printed in full tone using thermochromic ink on a self-adhesive label. In its inactive state, a single-coloured graphic indicator signifies the insulin has been stored within the recommended temperature range. Upon activation, the thermochromic ink undergoes a reversible transition from coloured to transparent state, revealing an underlying warning pictogram. This colour change provides an immediate visual alert that the insulin should be stored to a lower-temperature environment to preserve its efficacy. The study was conducted using two thermochromic printing inks formulated with pigment concentrations of 8%, 10%, and 12% in the binder. Each formulation was printed in one, two, and three ink layers to determine printing conditions for achieving optimal opacity and colorimetric properties. The results could provide recommendations for optimizing ink formulation and printing parameters in the production of functional thermochromic temperature indicators for specific purposes.

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KEY WORDS
Thermochromic ink, temperature indicators, functional printing, colorimetric properties

1. Introduction

Thermochromic printing inks are functional graphic materials that undergo a visible and, in many systems, reversible colour change in response to temperature. Their ability to provide an immediate visual indication without electronic components makes them suitable for the development of temperature indicators and other functional printed products (Lozo, 2012; Kulčar et al., 2010). Thermochromic elements can also provide added functional value in packaging and labelling by communicating information about temperature conditions to the user (Lozo, 2012; Vukoje et al., 2023). A widely used type of thermochromic printing ink is based on leuco-dye systems. These systems typically consist of colour-forming components that are incorporated into microcapsules, enabling their application in printing inks and producing a temperature-dependent transition between coloured and colourless or transparent states (Kulčar et al., 2010; Pu & Fang, 2022). The colour transition can be characterized using colorimetric parameters, while the optical properties of the printed layer are important for applications in which the thermochromic print has to conceal and subsequently reveal information printed underneath (Zhao & Li, 2019; Kavčič et al., 2019). The stability of thermochromic printing inks is also an important consideration for functional applications, particularly with respect to their behaviour under light and elevated temperatures (Friškovec et al., 2013). For a functional temperature indicator based on a multilayer

printed structure, the compatibility of the materials and the properties of the thermochromic ink are essential for achieving the required visual response. In the inactive state, the thermochromic layer should provide sufficient opacity to conceal an underlying graphic element. Upon activation, the thermochromic layer should become sufficiently transparent or decolorized to reveal the underlying information and provide an immediate visual signal. Such a principle can be applied to temperature-sensitive labels in which a visible warning pictogram is revealed when a predefined temperature condition is exceeded. Recent developments in thermochromic sensing also demonstrate the potential of printed thermochromic systems for temperature monitoring and visual temperature indication (Hakola et al., 2021; Jaszczak-Kuligowska et al., 2026). The functional behaviour of thermochromic prints depends on several printing and material parameters, including pigment concentration, number of printed layers and resulting ink-layer thickness. These parameters can influence the colorimetric and optical properties of the printed layer and consequently its suitability for a particular indicator application (Kulčar et al., 2010; Kavčič et al., 2019). Pigment concentration can affect the colour characteristics of the thermochromic layer, whereas the number of applied layers influences the amount and thickness of deposited ink and may consequently affect its opacity and ability to conceal the underlying graphic element (Zhao & Li, 2019; Kavčič et al., 2019; Tomašegović et al., 2021). These properties are particularly relevant for temperature indicators intended for applications where a clear distinction between normal and undesirable temperature conditions is required.

In this study, a functional printed temperature indicator was developed for monitoring the temperature conditions of insulin therapy during storage and use. Maintaining appropriate storage and handling temperatures is important for preserving the quality and efficacy of insulin therapy. A printed thermochromic indicator can provide a simple visual means of communicating changes in temperature conditions by revealing a warning pictogram after activation. The proposed multilayer indicator consists of a pictogram printed in full tone using leuco-dye-based thermochromic printing ink on a self-adhesive label. Two thermochromic printing inks were investigated using pigment concentrations of 8, 10 and 12% in the binder, with each formulation applied in one, two and three ink layers. The influence of pigment concentration and number of layers was evaluated in terms of colorimetric properties, optical density, and thickness of the printed ink layers. Particular attention was given to the functional response of the indicator, specifically the reversible transition of the thermochromic layer from the coloured to the transparent state and the subsequent visibility of the underlying warning pictogram. The investigated combinations of ink formulation and printing parameters were compared to identify suitable conditions for the development of the proposed functional temperature indicator.

2. Materials and methods

2.1. Materials and sample preparation

Blue and red leuco-dye-based thermochromic pigments (CHAOS TRADE, Poland) were used, with activation temperature ranges of 24–30 °C (blue) and 26–31 °C (red), respectively. The pigments were manually mixed with a transparent SEBASTAR binder (SEBEK INKS, Belgium) according to the manufacturer's instructions to obtain printable thermochromic inks while minimizing potential damage to the microcapsules. For each pigment, 100 g of thermochromic ink was prepared, with the pigment concentration in the binder set at 8%, 10%, and 12%. These concentrations were selected for investigation of their influence on the optical and colorimetric properties and functional performance of the temperature indicator. Both the pigments and the binder were water-based, ensuring their compatibility.

A polyester screen with a mesh count of 43 threads/cm, a mesh tension of 13.6 N, and a plain weave (PW) was used for screen printing. The screen was coated with AZOCOL Z 133 UV emulsion containing DIAZO NR.23 powdered stabilizer (KIWO, Germany), prepared according to the manufacturer's instructions. The prepared emulsion was applied to both sides of the screen and subsequently dried. A graphic film featuring a square motif was prepared for the production of the screen-printing plates. During exposure, the photosensitive emulsion polymerized in the exposed areas. The unexposed areas corresponding to the motif remained soluble and were removed during rinsing, forming the open stencil areas. After drying, the plates were ready for printing.

Recycled paper labels with a water-based adhesive were used as the printing substrate (HERMA, Germany). The labels carry the Blauer Engel environmental certification (Herma Sustainable Labels, 2026) and were supplied in A4 sheets (210 × 297 mm), arranged in seven columns with 27 labels per column. Each label measured 25.4 × 10 mm. The substrate was pre-printed using a laser printer with the indicator design. Three pictogram variations were developed in three colours (black, red, and blue) using Adobe Illustrator and Adobe InDesign (Figure 1). The pictograms were original designs based on symbols commonly used in pharmaceutical and safety signage. The thermochromic layer was subsequently intended to conceal the underlying pictogram in the inactive state and reveal it upon activation, forming the multilayer temperature indicator structure.



» **Figure 1:** *Design of the pictograms for the multilayer temperature indicator*

The TC inks were printed onto the pre-printed substrates using a semi-automatic screen-printing process. Each TC ink was printed at three pigment concentrations (8%, 10%, and 12% in the binder) and applied in one, two, and three ink layers, resulting in a total of 18 samples (Table 1).

Table 1
List of thermochromic ink samples prepared in the study

Sample	TC ink	Pigment concentration in binder	Number of TC ink layers
P8.1	blue	8%	1
P8.2	blue	8%	2
P8.3	blue	8%	3
P10.1	blue	10%	1
P10.2	blue	10%	2
P10.3	blue	10%	3
P12.1	blue	12%	1
P12.2	blue	12%	2
P12.3	blue	12%	3
C8.1	red	8%	1
C8.2	red	8%	2
C8.3	red	8%	3
C10.1	red	10%	1
C10.2	red	10%	2
C10.3	red	10%	3
C12.1	red	12%	1
C12.2	red	12%	2
C12.3	red	12%	3

2.2. Measurement methods

The thickness of the TC ink layer was measured for all 18 samples using a SaluTron D4-Fe thickness gauge. Ten measurements were taken at different locations on each sample. Densitometric measurements were performed using a Techkon Dens densitometer to determine the optical density of the TC ink layers. Ten measurements were taken for each sample at 23°C and 28% relative humidity. Spectrophotometric measurements were conducted to determine the L*, a*, and b* colorimetric values of the thermochromic prints at different temperatures. Samples printed with blue thermochromic ink were measured from 24 to 30°C and additionally at 32, 35, and 43°C, while samples printed with red thermochromic ink were measured from 26 to 31°C and additionally at 33, 36, and 42°C. Samples were heated using a Julabo heating system, while measurements were performed using an Ocean Optics 2000+ spectrophotometer equipped with an Ocean SR integrating sphere (ISP-30-6-R, 30 mm). Measurements were conducted under D50 illumination using a 2° standard observer and OceanView software. At each specified temperature, one sample of each TC ink, pigment concentration, and number of printed layers was measured.

3. Results and discussion

The densitometric measurements presented in Tables 2 and 3 show that the optical density of the TC prints was strongly influenced by the number of ink layers. For both blue (P8.1–P12.3) and red (C8.1–C12.3) TC inks, optical density increased consistently from one to three ink layers. The effect of pigment concentration was less uniform. For three-layer prints, optical density increased with increasing pigment concentration for both thermochromic inks. For the blue ink, the values increased from 1.369 at 8% to 1.486 at 10% and 1.506 at 12%, while for the red ink they increased from 1.476 to 1.479 and 1.572, respectively. In one and two-layer prints, some deviations from this trend were observed, particularly at 10% pigment concentration. Under the same printing conditions, the red thermochromic ink generally exhibited higher optical density than the blue ink, although a small difference in the opposite direction was observed for the 10% three-layer samples. This indicates that optical density depends on both the ink formulation and the number of ink layers (Viková & Vik, 2023). The standard deviations of ink-layer thickness and optical density were generally low. Most values were below 3% of the corresponding mean, with a few higher deviations in optical density. The observed variability may be related to the semi-automatic screen-printing process and the measurement procedure. These results confirm that the number of ink layers has a pronounced effect on optical density, while the effect of pigment concentration is less uniform and depends on the number of layers and TC ink formulation.

Spectrophotometric measurements were used to generate CIE a*/ b* chromaticity diagrams for the blue TC ink samples. The diagrams show the change in colour coordinates as a function of temperature. The a* axis represents the green–red component, whereas the b* axis represents the blue–yellow component. The negative b* values indicate the blue colour of the samples at the lower measurement temperatures. With increasing temperature, the a* and b* values progressively approach zero, indicating a decrease in chromaticity and a transition towards a colourless state. For the 8% pigment concentration (Figure 2a), this behaviour is observed for P8.1,

Table 2
Ink layer thickness and optical density of the blue TC samples

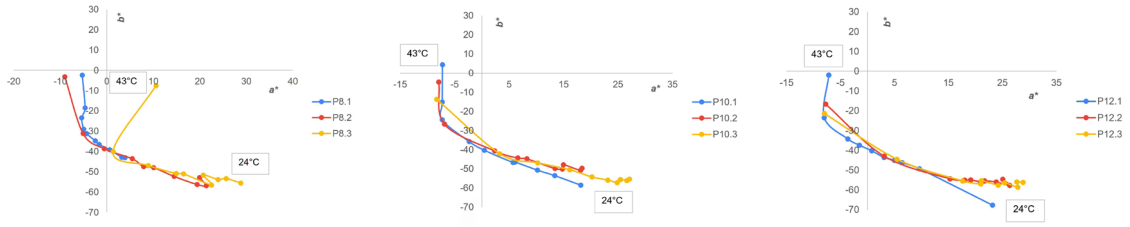
Blue TC samples	Ink layer thickness (µm)	SD	Optical density	SD
P8.1	183,6	3,27 (1,74%)	0,803	0,02 (2,49%)
P8.2	205	3,74 (1,82%)	1,324	0,02 (1,51%)
P8.3	241,6	4,17 (1,72%)	1,369	0,01 (1,09%)
P10.1	181,7	3,13 (1,72%)	1,01	0,03 (2,4%)
P10.2	221,2	3,19 (1,44%)	1,259	0,03 (2,4%)
P10.3	234,1	2,23 (0,95%)	1,486	0,01 (0,67%)
P12.1	193,7	4,55 (2,35%)	1,038	0,05 (4,81%)
P12.2	232,9	3,66 (1,13%)	1,335	0,001 (0,07%)
P12.3	245,4	3,44 (1,4%)	1,506	0,01 (0,66%)

Table 3
Ink layer thickness and optical density of the red TC samples

Red TC samples	Ink layer thickness (µm)	SD	Optical density	SD
C8.1	183	2,75 (1,5%)	1,074	0,01 (0,93%)
C8.2	199,8	4,71 (2,36%)	1,353	0,02 (1,48%)
C8.3	233,3	3,02 (1,29%)	1,476	0,02 (1,35%)
C10.1	191,7	1,95 (1,02%)	1,064	0,02 (1,88%)
C10.2	216,5	3,27 (1,51%)	1,286	0,02 (1,55%)
C10.3	235	3,65 (1,55%)	1,479	0,03 (2,03%)
C12.1	195,6	2,37 (1,21%)	1,199	0,01 (0,83%)
C12.2	229,6	4,4 (1,92%)	1,406	0,02 (1,42%)
C12.3	248	2,58 (1,04%)	1,572	0,02 (1,27%)

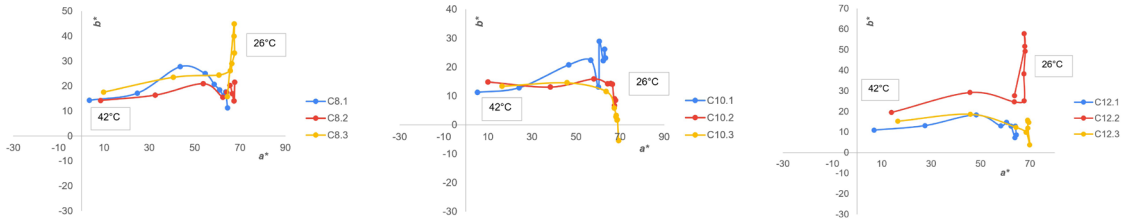
P8.2 and P8.3. The largest shift towards the achromatic region was observed for P8.1, whereas P8.2 and P8.3 retained more negative b* values at higher temperatures, indicating a lower degree of decolorization with increasing number of ink layers. A similar trend was observed for the 10% pigment concentration (Figure 2b), where P10.1 showed the greatest shift towards the achromatic region, while P10.2 and P10.3 retained higher colour saturation. For the 12% pigment concentration (Figure 2c), P12.1 again showed the most pronounced change in the a*/b* coordinates, whereas P12.2 and P12.3 retained more negative b* values at higher temperatures. Overall, the CIE a*/ b* chromaticity diagrams confirm the reversible thermochromic response of the blue thermochromic ink. The extent of decolorization was generally greater for samples printed with fewer ink layers, while samples with two and three ink layers retained a higher degree of chromaticity at elevated temperatures. These differences were particularly evident at the lower and upper ends of the investigated temperature range.

The a*/b* diagrams in Figure 3 show the temperature dependent changes in the colour coordinates of samples containing 8%, 10%, and 12% pigment at different numbers of ink layers for the red TC ink. At the initial temperatures, all samples exhibited positive b* values, indicating a colour position toward the yellow region. With increasing temperature, the colour coordinates changed considerably, with the a* values generally increasing and the b* values showing different trends depending on pigment concentration and number of ink layers. For the 8% pigment concentration (Figure 3a), C8.1 showed a moderate increase in b* followed by a decrease at higher temperatures, while C8.2 exhibited a relatively stable trend with smaller changes in b*. C8.3 showed a more pronounced variation, with a marked



(a) (b) (c)

» **Figure 2:** *CIE a*/b* diagrams of the blue TC ink containing 8% (a), 10% (b), and 12% (c) pigment in the binder, printed in 1, 2, and 3 ink layers*



(a) (b) (c)

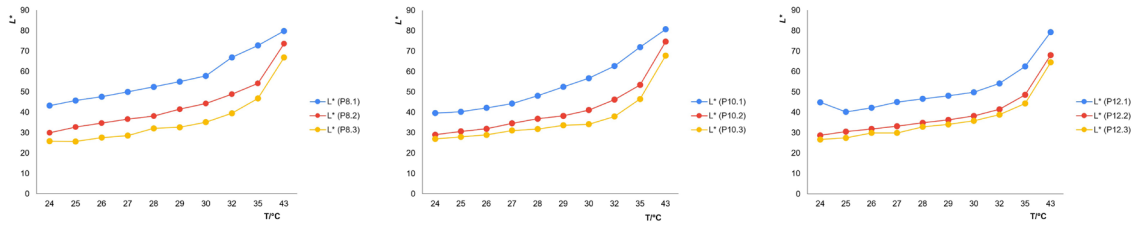
» **Figure 3:** *CIE a*/b* diagrams of the red TC ink containing 8% (a), 10% (b), and 12% (c) pigment in the binder, printed in 1, 2, and 3 ink layers*

increase in b* at higher temperatures. For the 10% pigment concentration (Figure 3b), C10.1 exhibited the most pronounced variation in both a* and b* values, including an increase in b* at intermediate temperatures followed by a decrease at higher temperatures. C10.2 showed a more gradual decrease in b*, whereas C10.3 exhibited a pronounced decrease in b* towards and below zero at higher temperatures. Among the 12% pigment samples (Figure 3c), C12.1 showed a gradual decrease in b* at higher temperatures, while C12.2 exhibited a pronounced increase in b*, reaching the highest values among the investigated samples. C12.3 showed a comparatively smaller variation, with b* remaining within a narrower positive range before decreasing at the highest temperatures. The results demonstrate that the temperature-dependent changes in a* and b* coordinates vary with both pigment concentration and number of ink layers. The differences are particularly evident at higher temperatures, where some samples show a decrease in chromaticity, while others retain or temporarily increase their b* values. This indicates that the thermochromic colour response of the red ink is influenced by the combination of pigment concentration and number of ink layers.

The L/T diagrams of the blue TC ink shown in Figure 4 indicate that the samples printed with one ink layer exhibited the highest lightness, regardless of pigment concentration in the binder. For all three pigment concentrations, the lightness of the two-layer samples was lower than that of the one-layer samples. At 8% and 10% pigment concentrations, the two-layer samples exhibited higher lightness than the corresponding three-layer samples. For the 12% pigment concentration, the lightness values of P12.2 and P12.3 are almost identical, indicating that the additional ink layer had little effect on the lightness of the printed sample. Each sample showed an increase in lightness with increasing temperature. This behaviour corresponds to the decolorization of the TC ink, during which the substrate beneath the thermochromic ink layer becomes increasingly visible. The increase in lightness therefore reflects the temperature-dependent transition of the thermochromic ink towards a more transparent state.

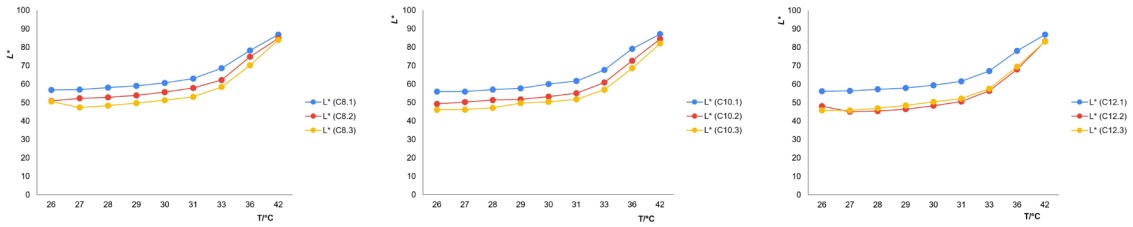
The temperature dependence of lightness of the red TC ink at all three pigment concentrations and number of ink layers is shown in Figure 5. The lightness values of the red TC ink samples were generally higher than those of the blue TC ink, while the differences between samples printed with different number of ink layers were relatively small. The most pronounced difference was observed among the samples containing 12% pigment concentration, where C12.1 exhibited the highest lightness, whereas C12.2 and C12.3 showed lower and nearly identical lightness values. For all red TC samples, increasing temperature resulted in increased lightness, with the change becoming more pronounced at higher temperatures. At lower temperatures, the lightness values were more stable and uniform. This behaviour is consistent with the thermochromic transition and increasing transparency of the thermochromic ink layer at elevated temperatures.

The temperature dependent properties of thermochromic inks enable their application in systems designed to



(a) (b) (c)

» **Figure 4:** *L/T diagrams of the blue TC ink containing 8% (a), 10% (b), and 12% (c) pigment in the binder, printed in 1, 2, and 3 ink layers*



(a) (b) (c)

» **Figure 5:** *L/T diagrams of the red TC ink containing 8% (a), 10% (b), and 12% (c) pigment in the binder, printed in 1, 2, and 3 ink layers*

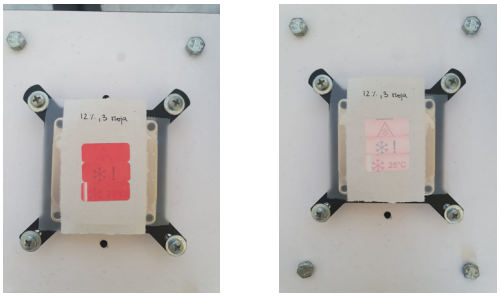
indicate predefined temperature conditions. Examples of the functional temperature indicators developed in this study are shown in Figures 6 and 7. The multilayer indicator printed on a self-adhesive label shown in Figure 6a demonstrates that the red thermochromic ink did not completely conceal the warning pictograms printed underneath the thermochromic ink layer. Consequently, the pictograms remained partially visible in the inactive state, which is not consistent with the intended function of the indicator. This effect was particularly evident for the pictograms printed in blue, whereas the red-line pictograms were less noticeable. With increasing temperature, the red thermochromic ink transitioned to a transparent state, resulting in clear visibility of all three warning pictograms in the activated state (Figure 6b). The appearance of a warning pictogram on packaging, for example for insulin therapy, could provide a visual indication that the product has been exposed to an elevated temperature and should be transferred to a lower-temperature environment.

In practical application, the blue thermochromic ink provided a more effective visual response. In the inactive state (Figure 7a), the blue thermochromic ink almost completely concealed all three warning pictograms, although their outlines remained slightly visible depending on the design and colour of the underlying printed elements. With increasing temperature, the thermochromic ink transitioned to a transparent state, revealing the pre-printed warning pictograms (Figure 7b).

These results demonstrate the feasibility of combining thermochromic ink layers with pre-printed graphic elements to develop a functional multilayer temperature indicator. With appropriate adjustment of the design and printing parameters of the underlying elements, the system could potentially be further developed for repeated thermochromic temperature indication.

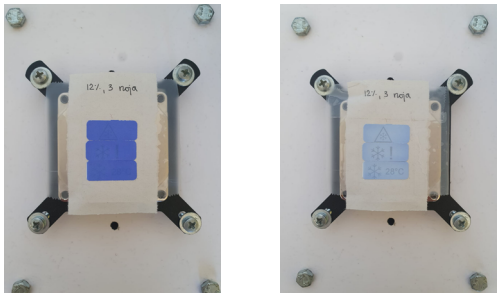
4. Conclusions

This study demonstrated the feasibility of developing a functional multilayer temperature indicator based on leuco-dye thermochromic printing inks. Two thermochromic inks, blue and red, were investigated at pigment concentrations of 8%, 10%, and 12% in the binder, with one, two, and three ink layers applied by screen printing. The results showed that the number of ink layers had a pronounced influence on ink-layer thickness and optical density, while the effect of pigment concentration was less uniform and depended on the number of layers and ink formulation. Spectrophotometric measurements confirmed the temperature dependent colour response of both thermochromic inks. Changes in L*, a*, and b* values demonstrated a transition towards a less chromatic and more transparent state with increasing temperature, although the extent of the change varied with pigment concentration and number of ink layers. The L/T diagrams further confirmed an increase in lightness at elevated temperatures, corresponding



(a) (b)

» **Figure 6:** *Thermochromic indicator printed with 3 layers of red TC ink with 12% of pigment in the binder, recorded at 26°C and 42°C*



(a) (b)

» **Figure 7:** *Thermochromic indicator printed with 3 layers of blue TC ink with 12% of pigment in the binder, recorded at 24°C and 35°C*

to the decolorization of the thermochromic ink layer and increased visibility of the underlying substrate. The practical evaluation showed that the blue thermochromic ink provided more suitable visual concealment of the underlying warning pictograms in the inactive state, while both inks enabled their clear visualization after activation. The developed multilayer structure therefore provides a simple visual means of indicating exposure to elevated temperature conditions. With further optimization of the graphic elements, pigment concentration, and number of ink layers, the proposed concept has potential for application in temperature-sensitive packaging and labelling, including applications related to insulin therapy.

5. Acknowledgments

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6. References

Friškovec, M., Kulčar, R. and Klanjšek Gunde, M. (2013) 'Light fastness and high-temperature stability of thermochromic printing inks', *Coloration Technology*, 129(3), pp. 214–222. DOI: 10.1111/cote.12020

Hakola, L., Vehmas, K. and Smolander, M. (2021) 'Functional inks and indicators for Smart Tag based intelligent packaging applications', *Journal of Applied Packaging Research*, 13(2), pp. 1–3. Available from: https://scholarworks.rit.edu/japr/vol13/iss2/3 [Accessed 27 September 2026].

Herma Sustainable Labels (2026) 'Labels made from recycled paper'. Available from: https://www.herma.com/label/products/sustainable-labels/labels-made-from-recycled-paper/ [Accessed 27 July 2026].

Jaszczak-Kuligowska, M., Sąsiadek-Andrzejczak, E., Safandowska, M., Kozicki, M., Florentino Madiedo, L., Barburski, M., Ranz, D. and Mallada, R. (2026) 'Thermochromic textile sensors for temperature measurements', *Measurement*, 257, 118698. DOI: 10.1016/j.measurement.2025.118698

Kavčič, U., Mraović, M., Bračko, S. and Muck, D. (2019) 'Printed thermochromic displays', *Coloration Technology*, 135(1), pp. 60–66. DOI: 10.1111/cote.12372

Kulčar, R., Friškovec, M., Hauptman, N., Vesel, A. and Klanjšek Gunde, M. (2010) 'Colorimetric properties of reversible thermochromic printing inks', *Dyes and Pigments*, 86(3), pp. 271–277. DOI: 10.1016/j.dyepig.2010.01.014

Lozo, B. (2012) 'Chromogenic indicators on packages'. In: *Innovative Packaging*. München: PTS, pp. 107–114.

Pu, Y. and Fang, J. (2022) 'Preparation and thermochromic behavior of low-temperature thermochromic microcapsule temperature indicators', *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 653, 129889. DOI: 10.1016/j.colsurfa.2022.129889

Tomašegović, T., Mahović Poljaček, S., Strižić Jakovljević, M. and Marošević Dolovski, A. (2021) 'Properties and Colorimetric Performance of Screen-Printed Thermochromic/UV-Visible Fluorescent Hybrid Ink Systems', *Applied Sciences*, 11(23), 11414. DOI: 10.3390/app112311414

Viková, M. and Vik, M. (2023) 'Transition Temperature of Color Change in Thermochromic Systems and Its Description Using Sigmoidal Models', *Materials*, 16, 7478. DOI: 10.3390/ma16237478

Vukoje, M., Krajnović, I., Kulčar, R., Cigula, T., Itrić Ivanda, K. and Jamnicki Hanzer, S. (2023) 'PCL Nanomodified Coating for the Protection of Thermochromic Prints on Packaging', *Materials Proceedings*, 14(1), 51. DOI: https://doi.org/10.3390/IOCN2023-14497

Zhao, Y. and Li, L. (2019) 'Colorimetric properties and application of temperature indicator thermochromic pigment for thermal woven textile', *Textile Research Journal*, 89(15), pp. 3098–3111. DOI: 10.1177/0040517518805390

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